Comparative Assessment of Environmental Impacts Associated with the Decommissioning of Fixed Offshore Platforms

by

Carolin Gorges

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FINAL YEAR PROJECT DISSERTATION

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Civil Engineering

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CERTIFICATION OF APPROVAL

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An project dissertation submitted to the
Civil Engineering Programme
Universiti Teknologi PETRONAS
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Approved by,

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January 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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CAROLIN GORGES

ABSTRACT

In the upcoming years, the number of offshore oil and gas installations, which have to be decommissioned, is going to increase around the world**,** as they approach the end of their productive lifetime. Decommissioning carries risks and safety problems beside ecological, economic as well as social effects. To assess the environmental impacts associated with the decommissioning process of offshore structures, life cycle assessment (LCA) is used. In accomplishing LCA**,** two main methods are applied to quantify those impacts which are process based method and Economic Input Output method (EIO). Both methods are studied and compared for their strength and limitations to obtain more reliable, representative and accurate results. The decommissioning options that are considered in the present study are complete removal and re-use as an artificial reef, whereas the environmental impacts of offshore decommissioning concerned in this paper are the total energy consumption and gaseous emissions such as carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulphur dioxide (SO_2). Using EIO method, the results of LCA show that the conversion to an artificial reef is the better decommissioning option in terms of energy consumption and gaseous emissions, whereas the process based LCA reveals the opposite results. The decommissioning activity which mostly contributes to energy consumption and gaseous emissions were identified, which is the marine vessel utilisation. The numerous results based on the decommissioning of Platform A, located in Malaysia, were compared with the quantified environmental impacts of decommissioning Heather Platform, installed in the North Sea, in order to find the relevant differences and coherences for further estimations of environmental impacts of future decommissioning projects. At the end of the present study, some suggestions of possible mitigation measures for environmental concerns in connection with the decommissioning of offshore platforms can be mentioned. Overall, the need to maintain the environment whether onshore or offshore is a global issue and affects the total humanity. To protect it for the future generations, the harm of the environment has to be reduced. In this case the environmental impacts could be less if the appropriate decommissioning option is found based on numerous results by using LCA tools.

Keywords: Environmental Impacts; Comparative Life Cycle Assessment; Decommissioning of Offshore Fixed Platforms; Process Based LCA, EIO-LCA

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LIST OF ABBREVIATIONS

AHT	Anchor Handling Tug
AR	Artificial Reef
BPEO	Best Practicable Environmental Option
CO_2	Carbon Dioxide
CS	Continental Shelf
DB	Dumb Barge
DSF	Deck Support Frame
EEZ	Exclusive Economic Zone
EIO	Economic Input-Output
EPA	United States Environmental Protection Agency
EQA	Environmental Quality Act
FPSO	Floating, Production, Storage, Offloading
GBS	Gravity Based Structure
GHG	Greenhouse Gases
ICCT	International Council on Clean Transportation
IMO	International Maritime Organization
ISO	International Standardisation Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MARPOL	Marine Pollution
NO_x	Nitrogen Oxide
OSPAR	Oslo and Paris Convention for the Protection of the North East Atlantic
PMU	PETRONAS Petroleum Management Unit
PSCB	Production Sharing Contract Block
RM	Ringgit Malaysia
SBO	Sabah Operations
SO_2	Sulphur Dioxide
SPAR	Single Point Anchor Reservoir
TLP	Tension Leg Platform
UNCLOS	United Nations Convention and the Law of the Sea
WB	Work Barge
WOW	Working on Weather

CHAPTER ONE

INTRODUCTION

This dissertation will define the background, problem statement, objectives and scope of study for the Final Year Project with the title: "Comparative Assessment of Environmental Impacts Associated with the Decommissioning of Fixed Offshore Platforms". Additionally a literature review mentioning the topics offshore platform types, decommissioning of offshore platforms, life cycle assessment, the used case study Platform A and Heather Platform will be stated. Afterwards the research methodology, project activities, key milestones and the project schedule will be provided. Subsequently the results of the conducted LCA methods will be presented, discussed, interpreted and compared depending on the decommissioning option, the LCA analysis and with the results based on Heather Platform. Finally, recommendations addressing the findings will be proposed and a conclusion be presented.

1.1 BACKGROUND OF STUDY

Malaysia is geographically separated into two similarly sized regions by the South China Sea which is located in the North West of Sabah and Sarawak where sedimentary basins signpost the existence of energy sources below the seabed. The exploration of the oil and gas resources in this region, which constitutes 68% of the oil and 86% of the natural gas of Malaysian reserves, has been accelerated towards deeper water due to depletion of their reserves in shallow water depth. Therefore in the forthcoming years, offshore decommissioning activity will be increased. Furthermore the existing offshore structures approach the end of their life-time use after about 20 to 30 years (Islam et al., 2012; Twomey, 2013).

There have always been debates regarding the environmental impacts during the decommissioning process and the disposal, the safety of the workers, the available technology and the costs required. To quantify the environmental impacts towards marine including the physical presence of vessels, the production of waste materials, atmospheric emissions, noise and vibrations life cycle assessment tools are used to find the most appropriate option for a specific structure to reduce the impacts and protect the environment. The major environmental impacts associated with offshore decommissioning are caused by the gaseous emissions, especially the greenhouse gas carbon dioxide emission, which is the main culprit for global warming produced by vessel utilisation, cutting operations and material transportation. For instance, the estimated amount of carbon dioxide of around 90,000 tonnes, released by the decommissioning process of an offshore platform in the North Sea, is comparable with the carbon dioxide emissions from electricity of 14,000 households in the United States during one year. The produced carbon dioxide will remain in the atmosphere for 100 to 200 years, absorb the heat energy and result in global warming and climate changes, which may lead among others to an increase of the sea levels and probable expansion of deserts (European Union , 2013; Ngu Pei Jia, 2013). Hence, it is very important to assess and to quantify the environmental impacts related to offshore installation decommissioning.

The LCA tools utilized in the present study are process based method and EIO method. Based on their respective strength and limitations of the both methods, the results evaluated will be compared and combined to get a more reliable, more representative and accurate outcome. process based method can be used to identify the particular decommissioning activity causing the greatest amount of total energy consumption and gaseous emission in order to be able to recommend options to minimise the environmental impacts. On the other hand the EIO method eliminates two major issues of the process based method which are the defined boundaries and circularity effects, while including the estimation of direct and indirect energy costs which may give a better overview of the environmental impacts of offshore decommissioning.

In the present study, two options for offshore decommissioning were analysed: the complete removal and the re-use as an artificial reef. The environmental impacts focused in this paper are the total energy consumption and gaseous emissions (CO_2, NO_x and SO_2) caused by offshore decommissioning. Input data required for the estimation of these parameters by using LCA tools were gained from the ‘Best Practicable Environmental Option (BPEO) for Platform A, SMV-A and EMV-A Decommissioning Study’, a Decommissioning Study Report about Platform A, from cost estimations and the documentation documents of the complete removal process of the case study Platform A. Furthermore conversion factors and an estimation of the mentioned environmental impacts were retrieved from a paper published by Side et al. (1997) about the decommissioning of Heather Platforms, as there was no data available for this specific platform or similar platforms of this size and in this region. Subsequently the output data received by using LCA tools regarding the environmental impacts of the decommissioning of the installation Platform A in Malaysia are compared with the determined results of the offshore structure Heather Platform placed in the North Sea, obtained from the stated published estimation from Side et al. (1997). Finally, relevant mitigation measures for environmental concerns arising in connection with the decommissioning of fixed offshore platforms are suggested.

1.2 PROBLEM STATEMENT

The decommissioning of offshore installations definitely causes harm to the marine life and the environment such as the atmospheric emission, energy consumption, noise pollution, vibrations and waste substances produced (Gibson, 2002). In the planning phase of a decommissioning project it is important to concern those environmental impacts to meet the growing public interest in environmental issues and to find the decommissioning process which would require less energy and produce less gaseous emissions. Especially in Malaysia there is limited information available on environmental impact assessment associated with offshore decommissioning. Current practices utilises qualitative measures rather than quantitative. A qualitative example is a ‘Best Practicable Environmental Option (BPEO) Study’ which assesses several decommissioning options with respect to technical feasibility, health & safety, environmental impact and cost criteria by applying a subjective ranking system.

Life cycle assessment is preferable to be performed as it may provide quantitative and structured comparisons between decommissioning options, while addressing the environmental impacts simultaneously. In addition, the decommissioning activity which is the main contributor to total energy consumption and gaseous emissions could be identified and recommendations could be proposed to minimise the environmental impacts of this particular decommissioning activity.

In the present study, the environmental impacts focused on atmospheric gaseous emissions (CO_2, NO_x and SO_2) and total energy consumption induced by two different decommissioning options for offshore structures, complete removal and the development of an artificial reef will be quantified and assessed by using two LCA tools, process based method and EIO method. The determined results provided by the LCA tools, associated with the installation Platform A in the South China Sea and Heather Platform in the North Sea are compared regarding the different options and structures. This will clarify which conditions and aspects are the most significant for the increase of environmental impacts due to decommissioning. On the basis of these identified results, a suggestion for relevant mitigation measures for environmental concerns related to the decommissioning of offshore structures could be proposed.

1.3 OBJECTIVES OF STUDY

In order to achieve the goal of this study the following objectives have been set:

1. To quantify the environmental impacts associated with the decommissioning of local offshore installations using life cycle assessment.

2. To compare and evaluate two LCA tools; process based method and EIO method.

3. To evaluate any apparent differences in environmental impacts and boundaries for decommissioning in Malaysia and the North Sea.

4. To suggest relevant mitigation measures for environmental concerns that arises in connection with the decommissioning of fixed offshore platforms.

The aim of this study is the quantitative measure of the Environmental Impacts of decommissioning Oil & Gas offshore platforms based on the case study Platform A. There has already been a qualitative assessment (BPEO Study) established to find the best option for decommissioning this structure. Technical criteria, environmental criteria, health & safety criteria and decommissioning cost estimation were taken into account, but without using LCA tools or any amount determination of environmental impacts (PETRONAS Research & Scientific Services Sdn. Bhd., 2006).

In this study, these values will be determined by using LCA tools, EIO method and process based method to find out if the recommended option would also be the result according to the numerous more objective research and to identify the decommissioning activity which mostly contributes to energy consumption and produced gaseous emissions. The obtained results are compared with the evaluated values of the decommissioning process of an offshore structure in the North Sea to be able to appraise the influence of several structural, locational and conditional differences between the observed installations. With respect to the outcomes of the study, the author may be able to state mitigation measures for environmental concerns which arise in connection with the decommissioning with offshore structures in order to minimise the impacts and to choose the appropriate option for the decommissioning for similar fixed platforms located in the shallow waters offshore Malaysia in the future.

1.4 SCOPE OF STUDY

The scope of the present study is to quantify the environmental impacts of local decommissioning offshore platforms using LCA tools EIO method und process based method. Thereby two options for offshore decommissioning, the complete removal and conversion to an artificial reef, will be analysed and compared, regarding their impacts on the marine environment. Besides that the environmental impacts concerned in this study are total energy consumption and the gaseous emissions (CO_2, NO_x and SO_2) produced during the decommissioning and the transportation process. Subsequently the results stated from the selected case study, an installation in Malaysia called Platform A, will be compared with those of an offshore structure placed in the North Sea, Heather Platform. Hence, relevant mitigation measures for environmental concerns arising in connection with the decommissioning of fixed offshore platforms will be suggested.

Data for the performance of EIO method are obtained from a cost estimation prepared by PETRONAS Petroleum Management Unit (PMU) for complete removal of Platform A. On the other hand, for process based LCA the data is provided by the BPEO study for Platform A and additional documentation components about the decommissioning process.

The present study neither includes the well abandonment and the decommissioning of pipelines and power cables, as they are usually left in place, nor the waste materials disposal processes due to technical complexity and safety concerns. The scope covers the environmental impacts resulted from marine vessel utilisation, the removal of the topside, jacket and boat landing structures including the dismantling, the material transport offshore and onshore as well as the materials left at sea and the platform material recycling.

1.5 SIGNIFICANCE AND FEASIBILITY OF STUDY

To date in Malaysia, there are approximately 300 shallow water fixed oil jacket offshore platforms, which are located in three regions: namely Peninsular Malaysia Operation (PMO), Sarawak Operation (SKO) and Sabah Operation (SBO). Already 48% of those platforms have exceeded their 25-year design life, thus, offshore decommissioning activity is set to rise in the near future. It is a fact that there are only a few offshore platforms, which have been decommissioned in Malaysia so far due to lack of regulatory framework and weak decommissioning plans.

It is undeniable that environmental impacts arise during the decommissioning operation. There will be among others, impacts on the marine environment, emissions to the atmosphere, effects on the soil, impacts associated with cleaning or removing chemicals from the installation offshore and not conclusively the consumption of natural resources and energy. The study and the quantitative assessment using LCA tools may be a benefit for the future since the steps of using the software associated with decommissioning of offshore platforms will be shown. Additionally, the results could be helpful for finding the decommissioning option with less environmental impacts for upcoming projects which are similar to the case study used in the present study Furthermore, there are various differences between offshore structures in Malaysian Sea and the North Sea closely related to the occurring environmental impacts such as the water depth, the usage, the weight and the type of the platform, the materials used, the equipment required as well as the duration of the decommissioning process. The results obtained by comparing the different structures and the parameters determined by using the LCA tools may be advantageous for other projects with similar conditions, regarding the possibility to reduce environmental impacts. Moreover, the values found in this research could provide incentive and motivation to find more efficient methods and new technologies for the decommissioning of offshore platforms.

The aim of accomplishing the present study is to produce a basic framework for future assessment of environmental impacts of offshore decommissioning activities in Malaysia based on the decommissioning of the used case study Platform A and the comparison to the selected Heather Platform in the North Sea.

This project is feasible within the scope and time given. The scope of this study and the main objectives had been clearly defined. Both, the LCA analysis for complete removal and re-use as artificial reef and the comparative assessment could be completed within the time frame with the defined boundaries and scope.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, the topics which have been reviewed are particularly on offshore platform types, the decommissioning of offshore installations with the subtopics of decommissioning laws and regulations, decommissioning options and the decommissioning process as well as decommissioning costs and the environmental impacts of offshore decommissioning. Besides that, the literature review on life cycle assessment is stated, outlining LCA framework and comparing the advantages and disadvantages of process based LCA and EIO method. The last part of this chapter contains the description of the selected case study Platform A, Malaysia and the chosen Heather Platform, North Sea for comparison purposes. The literature and past studies mentioned in this chapter are hoped to assist and to give better understanding on the work of the present study.

2.2 OFFSHORE PLATFORM TYPES

An offshore platform is a structure used to drill and produce oil and/or natural gas. There are two major types of offshore structures which are fixed and floating platforms. Fixed platforms are built on concrete and/or steel legs anchored directly onto the seabed, supporting a deck with space for drilling rigs and production facility, whereas floating structures are moored to the seabed , dynamically positioned by thrusters and are allowed to drift freely. Fixed structures are divided into four substructures the Jacket, Gravity Based Structure (GBS), Compliant Tower and Jack-up. Nevertheless the substructures for floating structures are the Tension Leg Platform (TLP), Semi-Submersible, Single Point Anchor Reservoir (Spar) and the FPSO (Floating, Production, Storage, Offloading). Figure 1 shows several platform types whereas a short explanation is given in Table 1 (Kurian, 2011).

Figure 1: Offshore platform types - 1,2) Conventional Fixed Platforms; 3) Compliant Tower; 4, 5)Vertically Moored Tension Leg and Mini-Tension Leg Platform; 6) Spar ; 7,8) Semi-Submersible; 9) FPSO (Wikipedia, 2013)

Table 1: Offshore platform types

FIXED PLATFORMS	Jacket	• Space framed structure with tubular members piled into seabed • Four to eight legs battered to achieve stability against toppling • Main piles are usually carried with the jacket and driven through the jacket legs into seafloor • Use limited to water depth of 150-180 m in harsh environment conditions • In more intermediate environments jackets had been installed in water depths up to 400 meter
	GBS	• Mostly concrete structure • Construction starts in dry dock → flooded • Remains in place on seabed because of self-weight
	Compliant Tower	• Narrow flexible framed structure supported by piled foundation • Conventional deck for drilling and production operations • Storage capacity • Used in water depths ranging from 400 to 900 meter
	Jack-up	• Three legged structure (tubular truss member) • Deck typically buoyant • Moved from place to place by transport barge and "jacked-up" above the sea at site • Used in water depths of less than 150 meter

FLOATING PLATFORMS	TLP	• Tied down to seabed by vertical steel tubes, called tethers → eliminates most vertical movement of structure • Used in water depths up to 1500 meter
	Semi-Submersible	• Legs of sufficient buoyancy to cause structure to float but weight sufficient to keep structure upright • Moveable from place to place • Held by anchors connected to mooring system • Used in water depth ranging from 100 meter to deepwater
	Spar	• Vertical floating system moored to seabed • Classic: one piece cylindrical hull • Truss: midsection composed of truss elements • Cell: multiple vertical cylinders • Centre of buoyancy above centre of gravity → low motion characteristics • Used in deep- and ultra-deepwater
	FPSO	• Ship-shaped structure with several different mooring systems • Integral oil storage capacity • Processing facility • Used in deepwater where fixed structures are not feasible

2.3 DECOMMISSIONING OF OFFSHORE INSTALLATIONS

Decommissioning is the process of planning, gaining an approval and implementing the cleaning, removal, disposal or re-use of an offshore oil or natural gas installation when it is no longer needed for its current purpose (Watson, 2004).

In the global context of the oil and gas industry, decommissioning became a concern after the 1995 Brent Spar controversy. Shell investigated several disposal options during 1991 to 1993 and decided to dump the oil platform with its 14,500 tons at the Atlantic Ocean. Greenpeace opposed this deep sea dumping method and occupied the platform and called for boycott of shell petrol stations. Although the disposal plan was actually approved by the UK government, Shell finally agreed to dismantle and recycle the platform onshore due to public pressure. (Shell International Limited, 2008).

In context with the oil and gas industry, decommissioning is an inherent part of the life cycle of an offshore platform. When the production of an oil or gas field becomes uneconomical due to among others high maintenance costs or low production volume, a decision needs to be made by the relevant regulatory agencies in conjunction with the platform operator to cease production, abandon the field and decommission the structure. As the most of the world wide platforms are located in the Gulf of Mexico, they have the most experience in decommissioning. From 1942 to 2010 around 3360 structures have been removed in this area. The UK Continental Shelf (UKCS) also exhibits a developing decommissioning business which is expected to increase in the upcoming years. In contrast in South East Asia any amounts of new offshore platforms have been developed during the last 30 years, but the decommissioning business is immature. There is a poor data base, understanding and less experience because only less than 10% of the facilities have been removed so far (Twomey, 2013). For instance Malaysia exhibits only three platforms decommissioning performed by PETRONAS. Based on the necessity of decommissioning of platforms which are going to reach the end of their productive life time it is essential to benefit from the experience of world-wide decommissioning and to research the possible options. The same applies for offshore installations in the Malaysian Sea, where decommissioning activities are forecasted to be increased in the near future. In Malaysia 48 % of the platforms have exceeded their 25-year design life. About 28 % of these installations are located off Sarawak (SKO), 12 % off Sabah region (SBO), and the remaining 8 % off Peninsular Malaysia (PMO) (Twomey, 2010). Thus, it is important to have a basic framework to assess the offshore decommissioning activities and options in Malaysia. Especially, regarding the environmental impacts caused by offshore decommissioning the assessment is future orientated since environmental issues are a big concern around the globe nowadays due to arising of global warming and ocean pollution. This study could be advantageous by providing numerous results using LCA tools to find the best solution for the decommissioning of Structures by causing less environmental impacts.

2.3.1 DECOMMISSIONING LAWS AND REGULATIONS

Because of the amount of decommissioning activities, guidelines and standards for the removal of offshore platforms were developed, especially by the United Kingdom and Norway as there are the world’s largest installations in some of the deepest water located (Gibson, 2002). In other countries the requirements are more loosely defined.

The first international removal standard was found in the 1958 Geneva Convention on the Continental Shelf, in which it is stated, that any installation which is abandoned or disused has to be entirely removed to ensure the protection of the environment and the prevention of interference with navigation and fishing. This Convention clearly outlines the state's obligations regarding their responsibilities and duties on the continental shelf (Hamzah, 2003).

In addition, internationally there are numbers of obligations concerning the decommissioning of offshore installations which have their origins in the United Nations Convention and the Law of the Sea (UNCLOS) established in 1982 and superseded the Geneva Convention. Article 60.3 notes, that any installation or structure which is abandoned or disused has to be entirely removed to ensure safety of navigation and fishing and protect the marine environment (Gibson, 2002). According to Twomey (2013) it became apparent that absolute entire removal would become unreasonably burdensome for the industry, as offshore oil and gas production moved into deeper water and more hostile environments during the 1960s and 1970s. The totally removal of those installations in deeper waters would be extremely costly and dangerous or impossible. Malaysia for its part does not subscribe to UNCLOS in case of dumping but to Conel Convention which allows leaving the offshore structure at the sea under certain conditions.

Furthermore, for instance the International Maritime Organization (IMO) developed a guideline for offshore decommissioning in 1989, named "Guidelines and Standards of the removal of offshore installations on the Continental Shelf and in the Exclusive Economic Zone" (International Maritime Organization, 1989). These guidelines require the entire removal of all abandoned or disused installations with less than 75m water depth and weigh less than 4,000 tonnes in air, excluding the deck and superstructure. Furthermore it is stipulated that the coastal state may determine that the installation needs not to be entirely removed, in the case where complete removal is not technically feasible or would involve extreme cost or unacceptable risk to personnel or the marine environment. Restrictively the guidelines state that a partial removal is only allowed if the substructure is lower than 55m from sea-level. Furthermore, the removal should be performed without causing significant adverse effects upon the marine environment. (International Maritime Organization, 1989).

Besides that, the Oslo and Paris Convention for the Protection of the North East Atlantic (OSPAR Convention) was formed in 1993. The regional Convention established regulations on the disposal and the dumping regarding decommissioning Offshore Structures including relevant aspects of waste management. (Poremski, 1998). In OSPAR Decision 98/3 the complete removal of steel installations with a jacket weight of less than 10,000 tonnes is required for reuse, recycling or final disposal while it is possible to remain the footings of steel jackets with a weight more than 10,000 tonnes in place. Equally for concrete structures there is the possibility to leave them in place wholly or partially (OSPAR Convention, 1998).

Aside from those international guidelines there are also few local regulations governing the decommissioning of offshore oil and gas installations and structures in Malaysia which follow IMO or OSPAR as those organisations boast long experience and expertise.

For instance the Environmental Quality Act (EQA) 1974 was developed (Percetakan Nasional Malaysia BHD, 2006). This act preliminary concerns with onshore activities but has also jurisdiction in territorial waters. It includes prohibition of the discharge of hazardous substances, mixtures containing oil, pollutants and wastes into Malaysian waters. Furthermore restrictions on the pollution of the atmosphere are stated (Bhoy, 2012).

In addition, there are the “PETRONAS decommissioning Guidelines (Malaysia) which cover all onshore and offshore installation within the Exclusive Economic Zone (EEZ) and Continental Shelf (CS) area. These guidelines require the removal of disused offshore installations and that the removal decision has to be made case-by-case. Furthermore it states that all factors particularly the legitimate interests of other users of the sea, the safety of navigation and the preservation of marine environment have to be taken into account in decommissioning assessment.

As there are various specifications regarding the complete removal of offshore structures, among others mentioning environmental issues, they have to be taken into consideration for oncoming decommissioning projects in order to protect the environment.

In contrast to the guidelines regarding the complete removal of offshore platforms there are the United Nations Environment Programme Guidelines for the Placement of artificial reefs. Artificial reefs have generally production or protection purposes and are constructed also by using oil and gas platforms. Those reefs which are constructed from structures originally built for another purpose but now obsolete or disused may accomplish environmental purposes (ecosystem or water quality management) and living marine resources (London Convention and Protocol, 2009).

2.3.2 DECOMMISSIONING OPTIONS

There are various options of decommissioning offshore structures and it has to be considered which option is the most appropriate in the specific case regarding the structure of the offshore platform (OGP Discussion Paper, 1995).

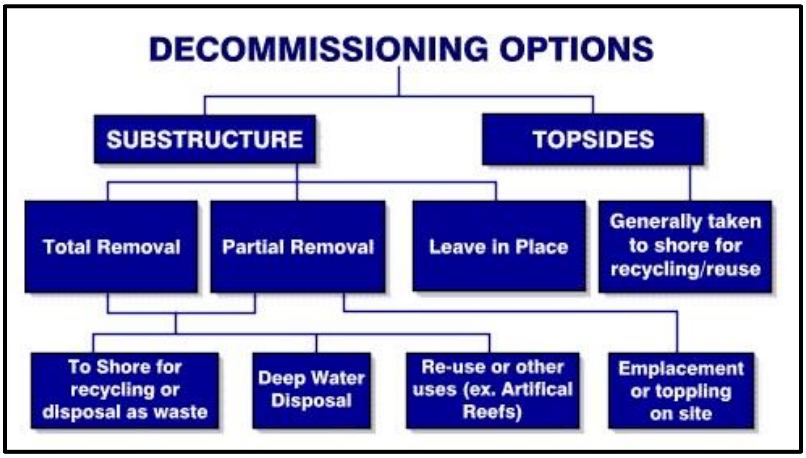


Figure 2: Decommissioning options for offshore structures

As put forward by Gibson (2002), in order to choose the best decommissioning option in any particular case, there are some points that have to be taken into consideration, which are the potential impact on the environment as well as human health and safety, the technical feasibility of the decommissioning plan. Furthermore the economic impact and public concerns have to be taken into account.

In the present study two decommissioning options which are complete removal in connection with the transportation onshore for recycling or disposal and the re-use as an artificial reef are compared by using LCA tools.

The complete removal requires the structure to be entirely removed by lifting either in one piece or in sections, depending on the size of the installation and the lift vessel’s capacity. The foundation piles are left in place from about 5 meter below the seabed. All components removed as parts (Christmas tree, wellhead, tubing, casings, conductor and risers) may be transported into deep water for subsea disposal or brought ashore to a fabrication yard for dismantling (Anthony et al., 2000). Recovered materials, which can be recycled (e.g. structural steel), may be sold to third party recycling concerns or dispatched for smelting and usable facilities are reused. Generally facilities, which cannot be reused or recycled, will be disposed of in accordance with applicable legal and PCSB Waste Management requirements (PETRONAS Research & Scientific Services Sdn. Bhd., 2006).

One of the few decommissioning projects performed in Malaysia is the complete removal of KETAM, a four leg jacket structure with water depth of 54 m installed 100 km off Labuan, Sabah (Muda, 2013).

An artificial reef is a submerged structure placed on the seabed to emulate some functions of a natural reef such as protecting, regenerating, concentrating and enhancing populations of living marine resources. The objectives of an artificial reef may include the protection and restoration of aquatic habitants. The categories artificial reefs are able to be grouped based of their functions are as follows (London Convention and Protocol, 2009):

- Environmental purposes (ecosystem management, restoration, water quality management)
- Living marine resources: attraction, enhancement, production, protection
- Scientific research and education
- Promotion of tourism and leisure activities
- Multi-purpose structures

The Rigs-to-Reef (RTR) is generally understood as the use of a decommissioned offshore oil and gas installation, which have been totally or partially submerged in-situ, or another selected location for the specific purpose of creating an artificial reef (Ruivo & Morooka). Studies indicated that oil and gas platforms have proven themselves to be excellent artificial reef materials because they have the characteristics including function, compatibility, durability, stability and availability require for this purpose (PETRONAS Research & Scientific Services Sdn. Bhd., 2006).

For the conversion to an artificial reef there are three methods; platform tow and place, platform topple in place and platform partial removal as shown in Figure 3 (Dauterive, 2000). As Platform A provides a water depth less than 55 m the partial removal of the structure is not an allowable option in this case, according to IMO.

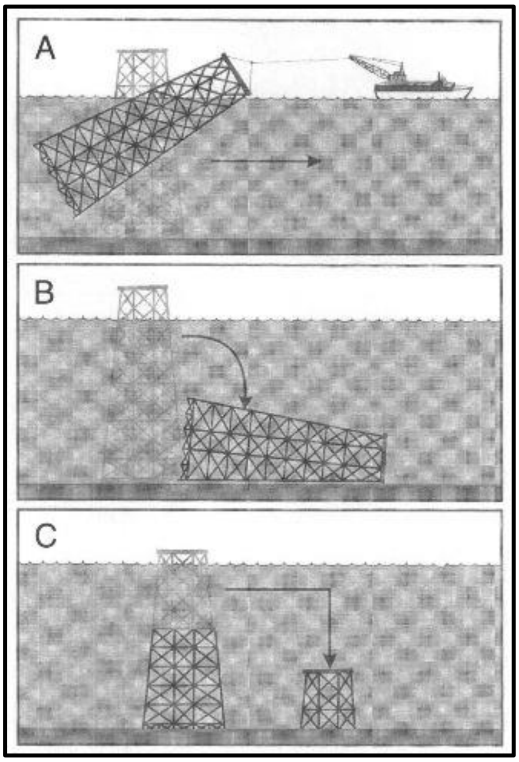


Figure 3: Methods of rig-to-reef

The conversion of offshore structures first arose at the Gulf of Mexico in 1987 where about 200 of the decommissioned offshore platforms have been converted to an artificial reef so far. Since then, they have proved being highly successful and cost-effective (Wan Abdullah Zawawi et al., 2012; Ruivo & Morooka).

The decommissioned platforms are ideal as artificial reefs as their open design attract fish and increase the amount of hard substrate required for coral communities. This results in a more complex food chain, leading to better fishery exploitations. On the other hand environmentalists claim this practice as a simple excuse for the disposal of used oil rig into the ocean which would lead to a certain degree of habitant damage, localised contamination and spreading of hydrocarbon invasive. However, Malaysia holds much potential in the conversion to artificial reef due to its relatively shallow water depths. One of two major rigs-to-reef programmes in Malaysian waters to date, is Baram-8, a single well 3-legged wellhead with a protection jacket located offshore of Sarawak in 2004 to add the Siwa Reef (Wan Abdullah Zawawi et al., 2012). The project required major cooperation from many sources including among others local and federal government, the Fisheries department, the Ministry of Environment and the Sarawak Tourist Board (Boothby, 2010).

2.3.3 DECOMMISSIONING PROCESS

The decommissioning Process can be divided into several stages:

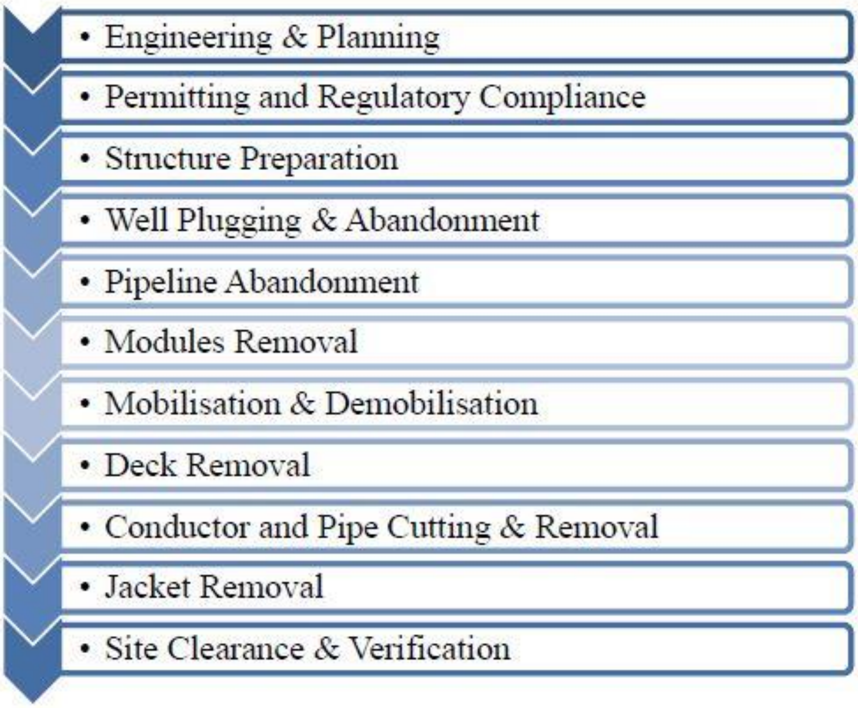


Figure 4: Primary activities in the decommissioning process (Kaiser et al., 2003)

After the project engineering and the cost assessment, federal and state regulatory permits for well plugging and abandonment, structure removal and site clearance verification have to be obtained. Subsequently the wells can be plugged and the facility is prepared for the removal including flushing and cleaning process components. Then, the pipelines are pigged or flushed, detached from the structure and capped. They are normally leave in-situ with the ends buried below the mud line. Components that have to be lifted separate from the deck are removed, before the deck can be cut and removed. Afterwards the conductors and piles are cut and pulled. The jacket is transported ashore by lift vessels for recycling or disposal. Finally the site has to be cleared with a trawling vessel or divers and the clearance has to be verified with a trawler (Kaiser et al., 2003).

The **planning and permitting phase** of decommissioning typically consists of a review of all contractual obligations and leasing, operating and production requirements or regulatory agreements. Each phase of the project has to be planed and the survey of the market for equipment and vessels is initiated. A site assessment for work requirements as well as a report on the options available, including the scope of work, which has to be performed, is executed (Kaiser, 2005).

The **plug and abandonment phase** has the purpose to destroy the permeability within the formation and stabilise the wellbore until geological forces can re-establish the natural barriers which existed before the well was drilled. These activities involve the setting of various cement plugs to prevent the migration of formation fluids within the wellbore or to the seafloor. Plugging and abandoning may occur before, during or after the removal preparation activities are completed, but it has to occur prior to cutting and removing the conductors (Kaiser, 2005).

Within the **preparation phase** the structure is prepared for removal and an inspection is implemented to determine the conditions of the structure to identify potential problems with the following decommissioning process. Additionally the equipment is cleaned, the modules are cut loose from the deck and the piping, electrical and instrumentations interconnections are cut. A module preparation for the lifting is also performed during this stage. The equipment, metallic debris is sent onshore for recycling while fluids used for cleaning and non-metallic debris are sent onshore for disposal to a landfill (Kaiser, 2005).

The **pipeline abandonment** may be conducted in place, if it does not constitute a hazard to navigation or commercial fishing operations, by flushing, filling with sea water, cutting and plugging and burring at least 1 meter below the mudline (Kaiser, 2005).

The **structural remova**l is typically the most expensive stage of decommissioning. The deck is normally cut from the jacket, lifted and placed on a cargo barge, secured and returned to shore for scrap or re-use. The interior of the piling is then cleared using water jets to remove the mud so that the cutting devices can be lowered 5 meter below the mudline. The piles and the conductor are cut at least 5 meter below the mudline and afterwards pulled and removed by a derrick barge crane. The conductor removal can take place as a part of the well plugging and abandonment or during the structure removal. Abrasive water jets or explosives are used to cut the conductors at the designated elevation. After the conductor and the piles have been removed, the jacket can be lifted and welded to a materials barge for transport to shore or a reef site. The jacket is either toppled-in-place, pulled over and placed on its side on the sea floor or cut in half of the water column (partial removal) where the bottom-half is left standing vertically and the top-half section is placed next to the base or removed to shore (Kaiser, 2005).

The **site clearance and verification** phase is the last stage of decommissioning. The site clearance involves the elimination of potentially adverse impacts from debris and seafloor disturbances, while verification is used to ensure, that the site is clear of obstructions. All abandoned well and platform locations in water depth less than 90 meter have to be cleared of all obstructions occurred because of oil and gas activities (Kaiser, 2005).

2.3.4 DECOMMISSIONING COST

Decommissioning usually is a long-term process. For instance, Philips Petroleum UK began to think about the decommissioning of their Platform named Maureen, a steel gravity drilling, production and oil storage platform installed in the U.K. Continental Shelf, with a water depth of about 96 m, already in 1993, but it was finally removed in 2001 (Gibson, 2002; Broughton et al., 1999). In addition the decommissioning process is very costly. The costs vary widely due to several factors, such as location and type (complexity) of the facility, number of structures to be removed, water depth and weight, the conditions associated with the wells and conductors, the decommissioning method, transportation and disposal options. The mobilisation and demobilisation costs of heavy lift vessels can also vary widely, depending on the origin of the derrick barge and the number of platforms to be decommissioned as a group (PETRONAS Research & Scientific Services Sdn. Bhd., 2006). For example, to decommission Harmony Platform, a jacket platform located in the Santa Barbara Channel, California in 366 m of water cost Exxon Company more than 155 million dollar (Irick, Ruhl, & Tucker, 1985; Proserv Offshore, 2010) and a study has conservatively estimated that the removal of the more than 200 offshore installations in Malaysia will PETRONAS cost around 8 billion Malaysian Ringgit (PETRONAS, 1997).

In Malaysia there is no specific decommissioning cost study conducted. The assessment of costs presented in the BPEO Study for Platform A is based on the experienced complete removal of Ketam Platform (1999-2004), which cost 62.44 million Malaysian Ringgit. The decommissioning cost for Platform A is expected to be much lower as it is a much smaller platform with minimum facilities (PETRONAS Research & Scientific Services Sdn. Bhd., 2006).

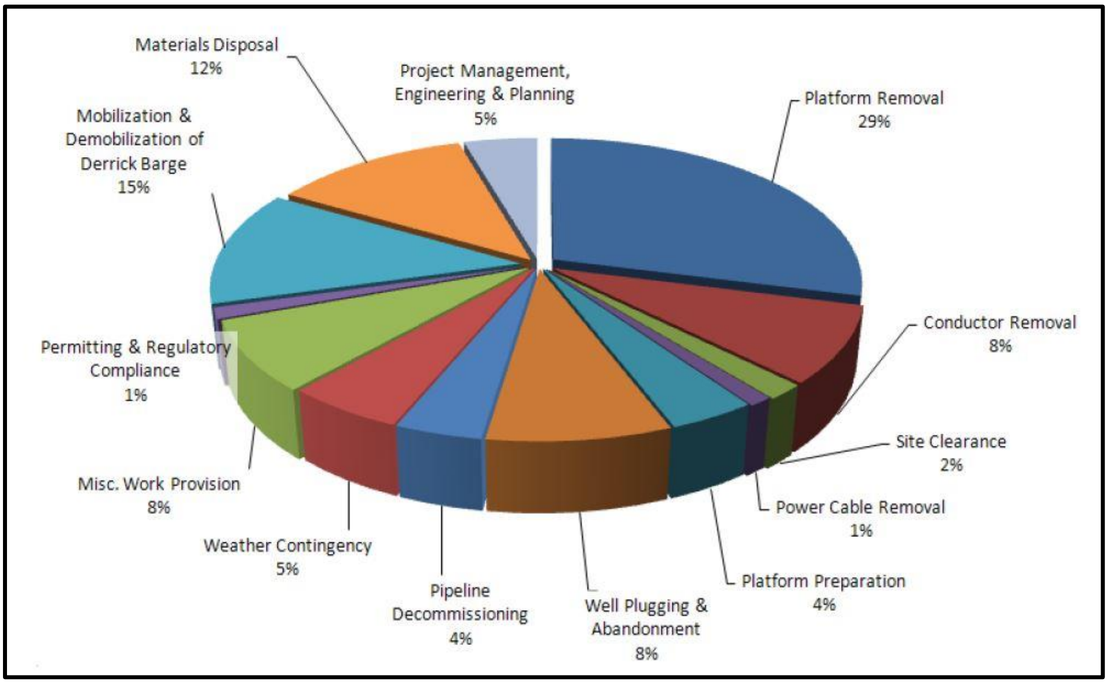


Figure 5: Decommissioning cost percentages by category (Proserv Offshore, 2010)

From Figure 5, which shows a percentage breakdown of total decommissioning costs, it becomes clear, that the Platform Removal, Mobilisation & Demobilisation of the Derrick Barge and the Material Disposal are the most cost intensive aspects of decommissioning with over 50 % of the whole process costs (Proserv Offshore, 2010).

2.3.5 ENVIRONMENTAL IMPACTS OF DECOMMISSIONING

Decommissioning of offshore installations has definitely impacts on marine life and the environment. These may be (PETRONAS Research & Scientific Services Sdn. Bhd., 2006):

- Impacts on Marine Environment
  - Vibration and noise due to machinery
  - “reef habitant” and fauna living on the jacket
- Emissions to the Atmosphere
  - Carbon Dioxide (CO_2)
  - Nitrogen Oxide (NO_x)
  - Sulphur Dioxide (SO_2)
- Effects on the Soil
  - Dredging and anchoring operations at the seabed
- Discharges and Impacts on Water Quality
  - Disturbance of sediments during dredging and debris removal operations (oily waste)
  - Accidental events as vessels grounding, collisions, dropped objects (fuel, chemicals)
- Impacts associated with cleaning or removing chemicals from installation (Offshore)
  - Chemical injection
  - Drilling fluids
- Impact of Re-use, Recycling (Onshore)
  - Material and waste disposal
  - Atmospheric emissions (material transport, material recovery processes)
- Consumption of natural resources and energy

Gaseous emissions primarily CO_2 but also smaller quantities of NO_x and SO_2 are produced during fuel combustion of the vessels used for cutting, lifting and transportation. These may cause local impacts to air quality and contribute to global climate change processes. For instance in 2011 CO_2 emissions developed from the UK offshore oil and gas industry represented 3.7 % of the total UK CO_2 emissions

(Oil & Gas UK, 2012). NO_x contribute to ground level ozone and particulate matter as well as other environmental effects such as reduction of the level of dissolved oxygen due to increased growth of underwater plants which can reduce fish and shellfish populations. Furthermore NO_x and SO_2 react in the atmosphere to form acid rain which accelerates the decay of building materials and paints (Marine Environment Protection Commitee, 2005).

Discharges to the sea include sewage and food waste and ballast water may occur during vessel operations and cause localised and transient deterioration in water quality, but no long-term hazards to bird and fish and other marine habitants. All discharges to the sea during the decommissioning process are permitted and regulated activities and the use of chemicals for cleaning purposes is controlled by Offshore Chemical Regulations (Oil & Gas UK, 2012).

Underwater noise is generated from vessel operations, especially from the use of dynamic positioning systems and from cutting and seabed excavation works. The noise produced during the decommissioning process is of lower intensity and shorter duration than the impacts caused by installation activities. However, the potential of noise to cause disturbance to marine animals should be assessed (Oil & Gas UK, 2012).

The p**hysical disturbance to the seabed** required to gain access for cutting operations may have impacts on the organisms that live in and on the seabed (Oil & Gas UK, 2012).

The **dismantling, recycling and disposal**, whether off- or onshore may result in visual impacts and generation of odour, noise and emissions due to reduction to small pieces, material transport and the recycling and disposal process. The extent to which these issues are significant depends on the location of the offshore installation in relation to the surrounding communities (Oil & Gas UK, 2012).

During cutting and lifting activities **objects** may be accidently **dropped into the sea** which, together with any infrastructure which is not removed, could interact with fishing gear. Hence, the site clearance and the verification is a very important part of the decommissioning process (Oil & Gas UK, 2012).

It is obvious that decommissioning of offshore platforms may have amounts of impacts to the marine environment, thus their estimation could be beneficial in order to be able to choose the most appropriate decommissioning option to minimise the negative environmental impacts.

In the study it is focused on the total energy consumption and gaseous emissions (CO_2, SO_2 and NO_x) which are determined by using LCA tools for two options mentioned above, the complete removal and the re-use as an artificial reef.

2.4 LIFE CYCLE ASSESSMENT

Nowadays, the public environmental awareness increases and the assessment of potential affects to the environment caused by industrial activities becomes more important. In addition society has become concerned about the issues of natural resource depletion and environmental degradation, so that the production or use of 'greener' processes and products is assessed to improve the companies' public image. The increased concern regarding environmental impacts of products and processes motivates the companies to investigate ways to minimise the environmental effects and adopt LCA to assess their products (Curran, 1996).

Typically, a product life cycle can be defined as a linear progression including the following stages (Green Design Institute):

- First, raw materials are extracted from the earth (e.g. ore, water and oil).
- Second, raw materials are processed into finished materials.
- Third, the materials are manufactured or assembled into a final product.
- Fourth is the use stage when a consumer has control of the product.
- Finally is the waste management stage or end-of-life stage when the product is broken down into component materials for remanufacturing or recycling, or is discarded.
- The sixth stage of distribution can be added as the materials and products are transported between stages.

The concept of life cycle assessment is to evaluate the environmental effects associated with any given activity from the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth. Therefore, the concept is often referred to as a "cradle-to-grave" approach used for industrial systems assessment (Ryding, 2011).

As stated by Consoli (1993), life cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy, materials used and wastes released to the environment to assess the impact of those energy and materials used and released to the environment. Included is the entire life cycle of the product, process or activity, encompassing extraction and processing of raw materials, manufacturing, transportation, distribution, use/re-use/maintenance, recycling and final disposal (Consoli, 1993).

LCA enables the estimation of the cumulative environmental impacts as a result of the whole product life cycle, provides a wide ranging view of environmental aspects and a more accurate picture about the environmental trade-offs in product and process selection (Ngu Pei Jia, 2013).

Historically LCA was used to calculate total energy consumption and predict future supplies of raw materials or resources in the 1960s and 1970s. For some cases they were combined with economic input-output models and became hybrid LCA to evaluate emissions and economic cost over their life cycle. Afterwards in the early 1990s LCA was being conducted for external purposes like marketing. Then the focus of LCA was shifted back to use for environmental optimisation as LCA provides quantitative and structured comparisons between alternatives or options by identifying the solution which may be preferred, while addressing environmental concerns simultaneously (Leontief, 1996).

2.4.1 LCA FRAMEWORK

The use of LCA could be beneficial in the development planning of offshore decommissioning by identifying those activities, where optimisation regarding energy consumption and reduction of gaseous emissions could be achieved.

Typically LCA framework comprises four phases as shown in Figure 6, which are Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation of the Result (Poremski, 1998).

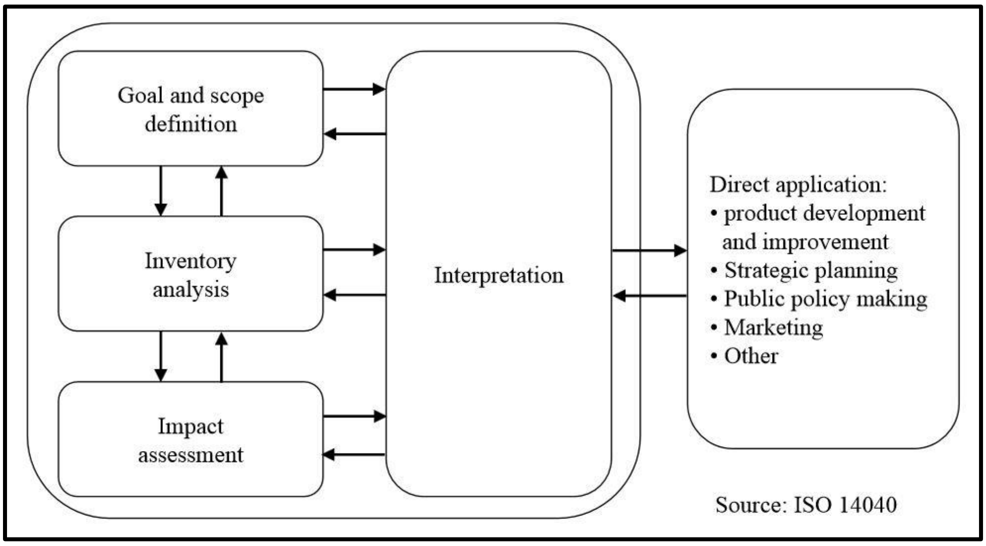


Figure 6: Life cycle assessment framework (American National Standards Institute, 1997)

As pointed out by Poremski (1998) an internationally harmonised and standardised approach is given in the International Standardisation Organisation (ISO) Standards:

- 14040 Basic Principles of life cycle assessment
- 14041 Goal and Scope Definitions and Life Cycle Inventory
- 14042 Life Cycle Impact Assessment
- 14043 Life Cycle Interpretation

The **goal and scope definition** is the first phase of LCA that defines the purpose of study, sets boundaries and establishes the product system and the functional unit. The goal and the scope have to be clearly specified to set stages for the entire LCA analysis in order to identify procedures, impact categories, data requirements and assumptions or limitations. A product system includes a set of unit processes that consume energy and release waste materials such as gaseous emissions into the environment, while a functional unit describes a quantitative reference to which in- and outputs are related. The system boundaries are based on the scope of study and the crucial factor for the quality of the inventory data. Data requirements set the level of details and specific data required (Scientific Applications International Corporation, 2006).

The second stage, the **life cycle inventory (LCI) analysis** comprises the quantification of energy and raw materials, atmospheric emissions, solid wastes and other releases for the entire life cycle of a product, process or activity. In this study the data collected includes energy or raw resources as input and the total amount of energy consumption and gaseous emissions as output which may be presented either in tabular or in graphic format (Scientific Applications International Corporation, 2006).

Life cycle impact assessment (LCIA), the third stage of LCA, includes the evaluation of the significance of potential environmental impacts using the results of the previous phase. The objective of this stage is to transform the inventory results into several impact categories. To state an example: LCIA combines the gaseous emissions of NO_x and SO_2 in one category; acidification. The procedural steps are: Inventory data are classified to their respective impact categories followed by the classification where inventory data are modelled within the impact categories and finally the impact categories are prioritised and weighted amongst each other (Poremski, 1998; Scientific Applications International Corporation, 2006).

The final stage is the **life cycle interpretation**, which includes the combination and interpretation of the findings from the inventory analysis and impact assessment. The major impacts could be determined from the whole life cycle and recommendations be made (Poremski, 1998).

Process based LCA is the most popular method amongst others. There are several tools such as GaBi, Umberto or SimaPro existing in the market which are suitable for conducting this type of LCA. These tools provide data from previous researchers on the environmental impact of materials and processes which can be applied by the user to form a system (Lehtinen, H. et al., 2011; Ngu Pei Jia, 2013).

The other method is EIO-LCA, which utilizes economic input-output tables and industry-level environmental data to construct a database of environmental impacts with reference to a selected economic value. (Green Design Institute). The boundary problem of process based LCA is solved as the EIO tables capture the interrelations of all economic sectors.

2.4.2 COMPARISON PROCESS BASED METHOD AND EIO METHOD

As stated previously, LCA tools used in this paper are process based method and EIO method. Process based method specifies the inputs (energy resources) and the outputs (emissions and wastes released to the environment) for each step over the entire life cycle, while EIO method estimates the energy resources required and the environmental emissions as a result from the whole process, and links it with monetary transactions (Green Design Institute). Whereas process based method is a simple and straightforward analysis of material and data for each life cycle stage, EIO method uses economic wide interdependencies by using input-output matrices in order to find the environmental impacts (Ishak, 2012).

Both methods have respective advantages and disadvantages. For instance, the results obtained from process based method are detailed and process specific. It also allows for specific product comparisons and the identification of the activity with the greatest contribution to the total energy consumption and gaseous emissions. EIO method on the other hand allows for systems-level comparisons and the derived results are economy-wide. In contrast to the provision of information on every commodity in the economy, process based method identifies weak points for process improvements. Otherwise, it tends to be time intensive and costly and is difficult to apply to new process design and has uncertainties in data. LCA using EIO method is difficult and has to link monetary values with physical units. Furthermore, it has uncertainty in data and includes incomplete and only limited number of environmental effects. (Hendrickson, 2006). On the other hand this method eliminates two major issues of process based LCA; defined boundaries and circularity effects. As the transactions and emissions of all industry sectors among all the other industry sectors are included, the boundaries for EIO model are very broad and inclusive. Since the EIO model includes the self-sector transaction, the circularity effects are included in the analysis. (Green Design Institute). For instance, the EIO model provided by the Green Design Institute (www.eiolca.net) includes even energy consumed by iron ore mining as the pig iron is needed in the steel recycling process, which proved that EIO-LCA has a broad boundary and includes circularity effects. This point is not included in the process based LCA and considered as one of the circularity effects for the recycling process (Ngu Pei Jia, 2013).

To provide an overview on the advantages and disadvantages of the described LCA methods, they are stated in table format (Green Design Institute):

Table 2: Advantages of process based LCA and EIO-LCA

	Process-Based LCA	EIO-LCA
Advantages	results are detailed, process specific	results are economy-wide, comprehensive assessments
	allows for specific product comparisons	allows for systems-level comparisons
	provides for future product development assessments	provides for future product development assessment
	Identifies areas for process improvements, weak point analysis	uses publicly available, reproducible results
		Provides information on every commodity in economy

Table 3: Disadvantages of process based LCA and EIO-LCA

	Process-Based LCA	EIO-LCA
Disadvantages	setting system boundary is subjective	product assessment contain aggregate data
	time intensive and costly	process assessment difficult
	difficult to apply to new process design	must link monetary values with physical units
	use proprietary data	imports treated as products created within economic boundaries
	cannot be replicated if confidential data are used	availability of data for complete environmental effects
	uncertainty in data	uncertainty in data

For the present study, both methods mentioned above are studied and used to evaluate the environmental impacts of the decommissioning options complete removal and conversion to an artificial reef. The author may be able to identify the decommissioning activities with the greatest contribution to the concerned environmental impacts associated with the decommissioning based on detailed results retrieved from process based method. On the other hand more reliable accurate results for total energy consumption and atmospheric emissions could be achieved by EIO analysis since it includes circularity effects and broad boundaries. To gain an accurate outcome the results of both are combined and compared to eliminate the limitations.

In conclusion life cycle assessment is an important and appropriate tool to quantify the environmental impacts of decommissioning of offshore structures. The results could be used to find alternatives for the decommissioning options analysed to reduce the amount of impacts acting on the environment.

2.5 RESEARCHED OFFSHORE PLATFORMS

2.5.1 CASE STUDY: PLATFORM A, MALAYSIA

A case study can be defined as a research strategy, an empirical investigation of a phenomenon in real-life context. In this paper a case study is used to identify the Environmental Impacts based on a decommissioning Process of a specific fixed offshore platform using the following LCA tools: process based method and EIO method. By reference to this case study, it should be pointed out which Environmental Impacts take place during the decommissioning Process and in which amount. Afterwards, the quantitative results regarding this case study can be compared with the Environmental Impacts of the decommissioning of another, totally different Offshore Installation in the North Sea. Moreover, the outcome could be used to find alternative Options of decommissioning for similar projects to mitigate the Environmental Concerns that arises in Connection with decommissioning of fixed offshore platforms.

The Offshore Structure, used as case study, named Platform A was a single pile wellhead production jacket located at Semarang Field, a part of Sabah Operations (SBO). It was installed approximately 50 km north-northwest of Labuan, Sabah in Malaysia with a water depth about 10.5 m. It had been constructed in March 1975 and was one of 17 production and drilling platforms fixed in the field, operated by Production Sharing Contract Block (PSCB), to accommodate the increasing production due to increasing energy demand. The production capacity of the field for oil was around 1,700 to 3,500 barrel per day and for gas approximately 16 to 20 million standard cubic feet per day (PETRONAS Research & Scientific Services Sdn. Bhd., 2006). Figure 7 shows the location of Platform, whereas Figure 8 presents the installation from all cardinal directions (Allied Marine & Equipment Sdn. Bhd., 2009).

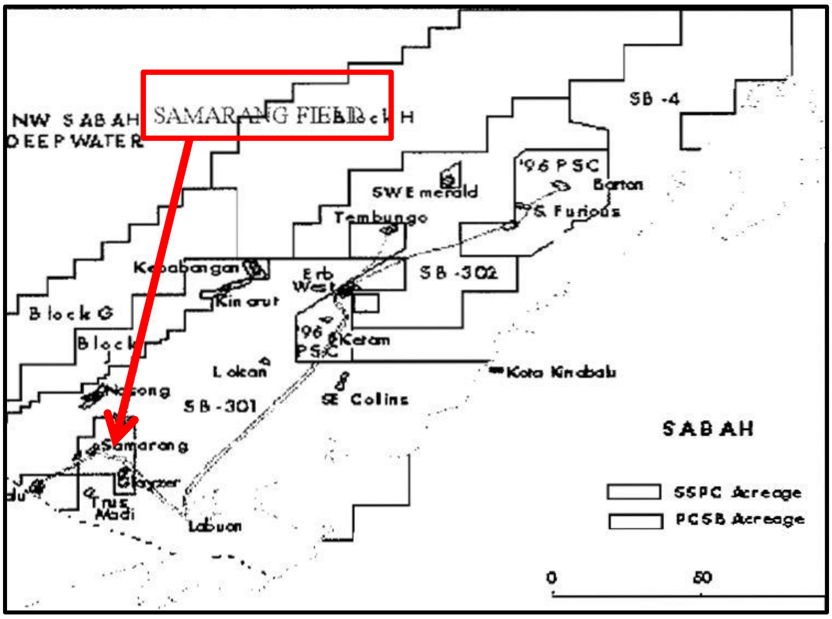


Figure 7: Location Samarang Field (PETRONAS Research & Scientific Services Sdn. Bhd., 2006)

Figure 8: View of Platform A from the North and South

Figure 9: View of Platform A from the East and West

The facilities of the offshore platform included (PETRONAS Research & Scientific Services Sdn. Bhd., 2006):

- 42” x 1.25/1.00” WT Main pile from EL (+) 34’ to 5’ below mud line
- 30” x 1.25/1.00”WT Insert pile from EL (+) 35’to 5’ below mud line
- 21.6 m 32” x 0.75” WT Conductor Casing (27.9 tonnes) with Christmas Tree
- Platform main Deck / Wire line Deck.
- Cellar Deck / Wellhead Service Platform
- Boat Landing and access Stairwell
- One 22.1 m 6” Production Riser and Conductor
- Topside well / Valve Assembly
- 244 m of 6” pipeline to SMP-A

The Structure had stopped its operations in 1986 because of structural deficits. Therefore it had been decided that the platform was not suitable for the operational requirements and therefore needed to be decommissioned, which was realised in

April 2012 by cutting the platform into 3 sections; the boat landing (16 tonnes), topside (28 tonnes) and jacket (32.5 tonnes). (Akram, 2012).

Figure 10: Removal of Platform A (Abdullah, 2013)

To be able to select a disposal option for the installation a Best Practicable Environmental Option (BPEO) Assessment Study had been prepared under considerations of Technical Criteria, Environmental Criteria, Health and Safety and the decommissioning Cost Estimation. Regarding the Topside, the Deck and the Jacket Structure three decommissioning Options had been compared: Refurbish/Re-use, Onshore Recycle/Disposal and artificial reef. In conclusion, complete removal had been chosen (PETRONAS Research & Scientific Services Sdn. Bhd., 2006).

In the present study the selected option complete removal and the option Re-use as an artificial reef will be compared concerning the Environmental Impacts of decommissioning Platform A. Although the decision has already been made and the structure is decommissioned, this study may be beneficial for future similar decommissioning projects. The BPEO decommissioning Study is just a subjective qualitative assessment for decommissioning Platform A. In contrast this study takes quantitative measures of atmospheric emissions and the energy consumption into account by using LCA tools: process based method and EIO method. Afterwards the results of life cycle assessment and the decision made in BPEO Assessment Study are compared, regarding the selected decommissioning Option.

2.5.2 HEATHER PLATFORM, NORTH SEA

Heather Platform, shown in Figure 10, is located in Block 2/5 in the U.K Sector of the North Sea, 145 km east of the Shetland Islands and operated by Unocal Britain Limited. The field has been developed with single drilling, production and quarters platform and has a water depth of 143 m. The platform has a maximum height of 236 m and consists of modular topsides sitting on top of the deck support frame supported by a steel jacket substructure, which is piled to the seabed (Hustoft & Gamblin, 1995).

Figure 11: Heather Platform

The topsides comprise of drilling, production, utility and quarter modules and two flare boom. The total dry weight of the topside is estimated at 12,300 tonnes. The jacket is an eight leg tubular space frame, steel structure which is supported by six piles connected to each of the four corner legs. The estimated weight of the jacket is approximately 17,000 tonnes; the weight of the 41 well conductors located within the jacket is approximately 4,300 tonnes to mud line. The estimated growth on the jacket is estimates to weigh 2,000 tonnes (Side et al., 1997)

2.5.3 COMPARISON PLATFORM A AND HEATHER PLATFORM

Table 4: Differences Platform A and Heather Platform

Criteria	**Platform A**	**Heather Platform**
Location	South China Sea – Sabah Malaysia	North Sea – Shetland Islands
Installation Date	1975	1978
Operator	PCSB	Unocal British Limited
Structure Type	Jacket	Jacket
Personnel	unmanned	manned
Accommodation	NO	YES
Total Height	approx. 25 meter	236 meter
Total Weight	80.5 tonnes	_
Water Depth	10.5 m	143 m
Service	Oil Production	Drilling Production
Average Oil Production Capacity	1700 to 3500 barrel oil per day (Semarang Field)	36,000 barrels per day
Gas Production Capacity	16 to 20 million cubic feet per day (Semarang Field)	_
Topside	Supported by one single leg which is welded to the single pile driven into the seabed	Sitting on a deck support frame (DSF) supported by steel jacket substructure piled to seafloor
Topside Facility	Jib Crane 4 inches flowline	“lift units”: drilling, production, utility and quarter modules, 2 flare booms (each 52 m long), 1 drilling derrick, 2 diesel powered pedestal cranes
Topside Weight	28 tonnes	12,300 tonnes (including DSF)
Jacket	1 single support leg, welded to the main pile an 9.14 m	8 leg, tubular space frame steel structure

	from the mean sea level	
Piles	1 single pile (42 inches, 16.8 tonnes) with 1 internal 30 inches diameter insert pile driven 16.764 m into seabed (12.08 tonnes)	6 piles connected to each of the 4 corner legs
Jacket Weight	32.5 tonnes	17,300 tonnes (including the piles and grout)
Well Conductor	1 (6 inches)	41
Conductor Casing Weight	27.9 tonnes	_
X-Mass Tree	1 (2.7 tonnes)	_
Riser	1 (6 inches)	2 (16 inches)
Conductor & Riser Weight	0.9 tonnes	4,300 tonnes to mud line
Marine Growth	_	2,000 tonnes
Caisson	NO	9 for miscellaneous services (e.g. process sump, utility sump, seawater lift caisson etc.), supported by jacket structure
Deck	Platform Main Deck/Wire Line Deck Cellar Deck / Wellhead Service Platform 14 inches height 16.2 tonnes	3 main deck levels (10,000 m²)
Boat Landing / Access Stairwell	16 tonnes	_
Helideck	NO	YES
Pipe	244 meter (6 inches)	32,000 m (6 inches) oil pipeline 19,000 (6 inches) gas pipeline

Table 4 comprises several differences between Platform A and Heather Platform with respect to basic information, capacity, component weights and structural characteristics. The unmanned, single legged Platform A has a water depth of 10.5 meter where Heather Platform provides accommodations and is supported by 8 legs, with a water depth of 143 meter. While the jacket and the topside of Platform A weigh 32.5 tonnes and 28 tonnes respectively, Heather Platform consists of a jacket and topside with weights of 17,300 tonnes and 12,300 tonnes respectively. Whereas Platform A with a total height of 25 meter had an average oil production capacity of 1,700 to 3,500 barrels per day, the 236 meter high Heather Platform is able to produce 36,000 barrels per day. It becomes clear, that there are big structural differences between the installations with different location (Hustoft & Gamblin, 1995; PETRONAS Research & Scientific Services Sdn. Bhd., 2006; Allied Marine & Equipment Sdn. Bhd., 2009).

2.6 SUMMARY

In this chapter the literature review particularly on offshore platform types, the decommissioning of offshore installations, the concomitant laws and regulations, various decommissioning options and the process itself as well as decommissioning costs and the environmental impacts of offshore decommissioning was presented. Besides that, the literature review on life cycle assessment was stated, outlining LCA framework and comparing the advantages and disadvantages of process based LCA and EIO method. The last part of this chapter contained the description of the selected case study Platform A and the chosen Heather Platform for comparison purposes. In the next chapter, the author will present the research methodology applied in this study, mainly the implemented project activities, the key milestones, the Gantt chart and the LCA methodology.

CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

The main objective for this chapter is to describe the methodology used for the study. The main problem and the objectives were outlined in Chapter One and will be taken up again in this chapter. After that the research methodology and project activities will be shown in Figure 12 and 13 respectively. Furthermore, in this chapter key milestones and the Gantt chart of the project will be presented. In the last part of this chapter the detailed breakdown of the LCA methodology used in this study will be elaborated.

3.1.1 RESEARCH PROBLEM

Offshore structure decommissioning definitely causes environmental impacts which have to be assessed and quantified since the public awareness on environmental issues increases. However, there is minimal information and framework published and less numerical research done. LCA analysis can be performed to provide quantitative and structural comparison between different decommissioning options and their environmental impacts. Therefore the aim of this study is to develop a basic framework to assess environmental impacts associated with offshore decommissioning in Malaysia.

3.1.2 RESEARCH OBJECTIVES

The objectives of the study are:

i) *To quantify the Environmental Impacts of local decommissioning Offshore Installations using Life Cycle Assessment.*
Platform A, a Jacket Platform located offshore Sabah in the South China Sea, is selected as a case study. The environmental impacts

produced during offshore decommissioning are quantified by performing life cycle assessment based on two decommissioning options; complete removal and conversion to an artificial reef. Gaseous emissions produced (CO_2, SO_2 and NO_x) are the main concern, which causes harm to the marine environment. The detailed LCA methodology will be further explained in this chapter.

ii) *To compare and evaluate two LCA tools; process based method and EIO method.*

The retrieved results by conducting the two LCA tools process based- and EIO method respectively will be compared and the applicability for this study be evaluated.

iii) *To evaluate any apparent Differences in Environmental Impacts and Boundaries for decommissioning in Malaysia and the North Sea.*

In order to address this objective, the results obtained from process based- and EIO method regarding the assessed decommissioning options, complete removal and conversion to an artificial reef, will be interpreted in the next chapter. Those outcomes will be further compared with the gaseous emissions and the total energy consumption associated with the decommissioning of Heather Platform, located in the North Sea.

iv) *To suggest relevant Mitigation Measures for Environmental Concerns that arises in Connection with the decommissioning of fixed offshore platforms.*

For this objective, based on the results attained by process based LCA, the decommissioning activity, which is the main contributor for energy consumption and gaseous emissions could be identified and mitigation measures and recommendations proposed in the following chapter to reduce the environmental impacts associated with decommissioning of Fixed Offshore Structures.

3.2 RESEARCH METHODOLOGY

After the selection of the project title "Comparative Assessment of Environmental Impacts Associated with the decommissioning of Offshore Fixed Platforms", the main relevant and feasible objectives and the scope of study were identified. Subsequently, the author researched online and read through journals and papers on life cycle assessment, decommissioning Options for offshore platforms, their environmental impacts, and the LCA tools (EIO method and process based method), which will be used in this study. Afterwards, the data and information required for the analysis will be collected by using internet and available resources provided by the university. Further the collected data will be analysed using the LCA tools mentioned above. After the output results are compared and discussed regarding the two LCA tools, the differences between the Environmental Impacts of decommissioning in dependence of the location of the Offshore Structures and the possible mitigation measures, a conclusion will be made. Finally the author will proceed with the report writing to record all the findings.

The research methodology applied in the present study is presented in Figure 11. The project activities are shown in Figure 12.

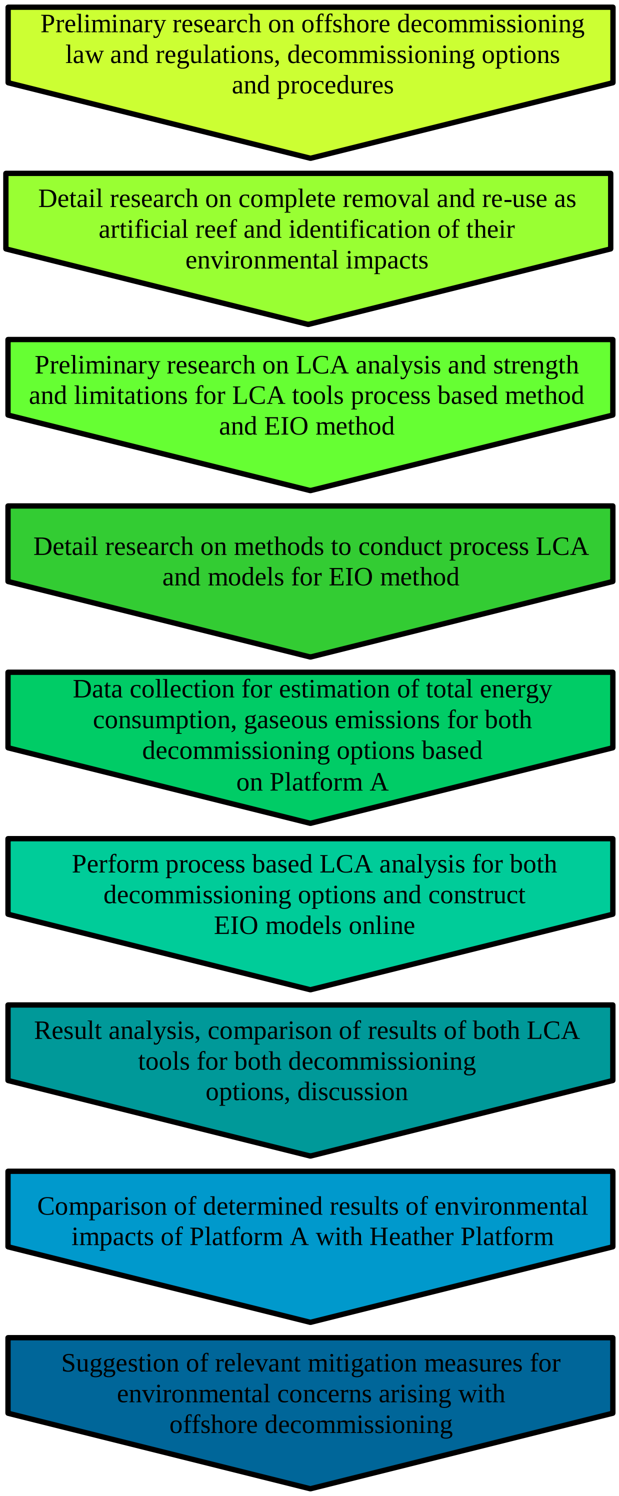


Figure 12: Research methodology applied in this study

3.3 PROJECT ACTIVITIES

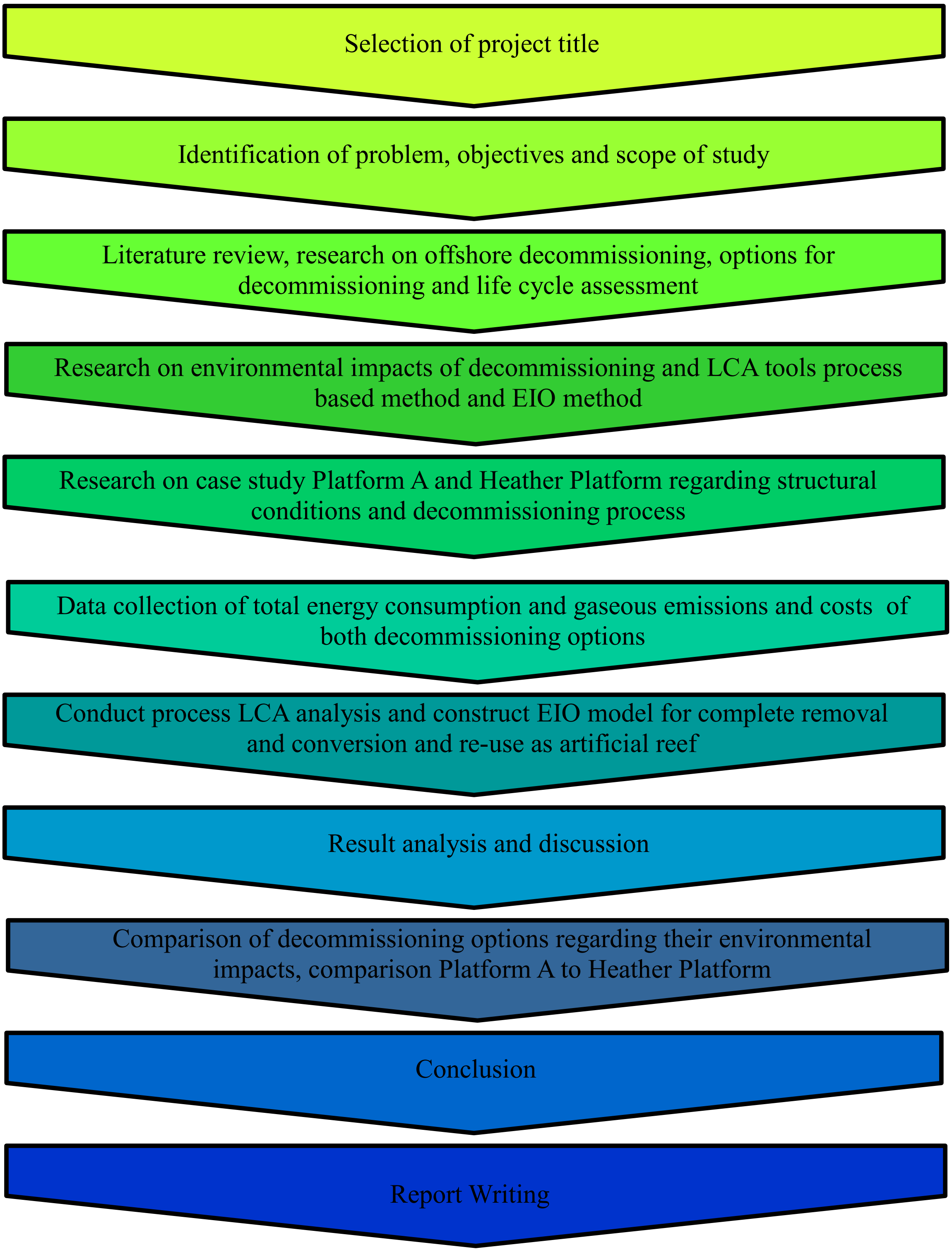
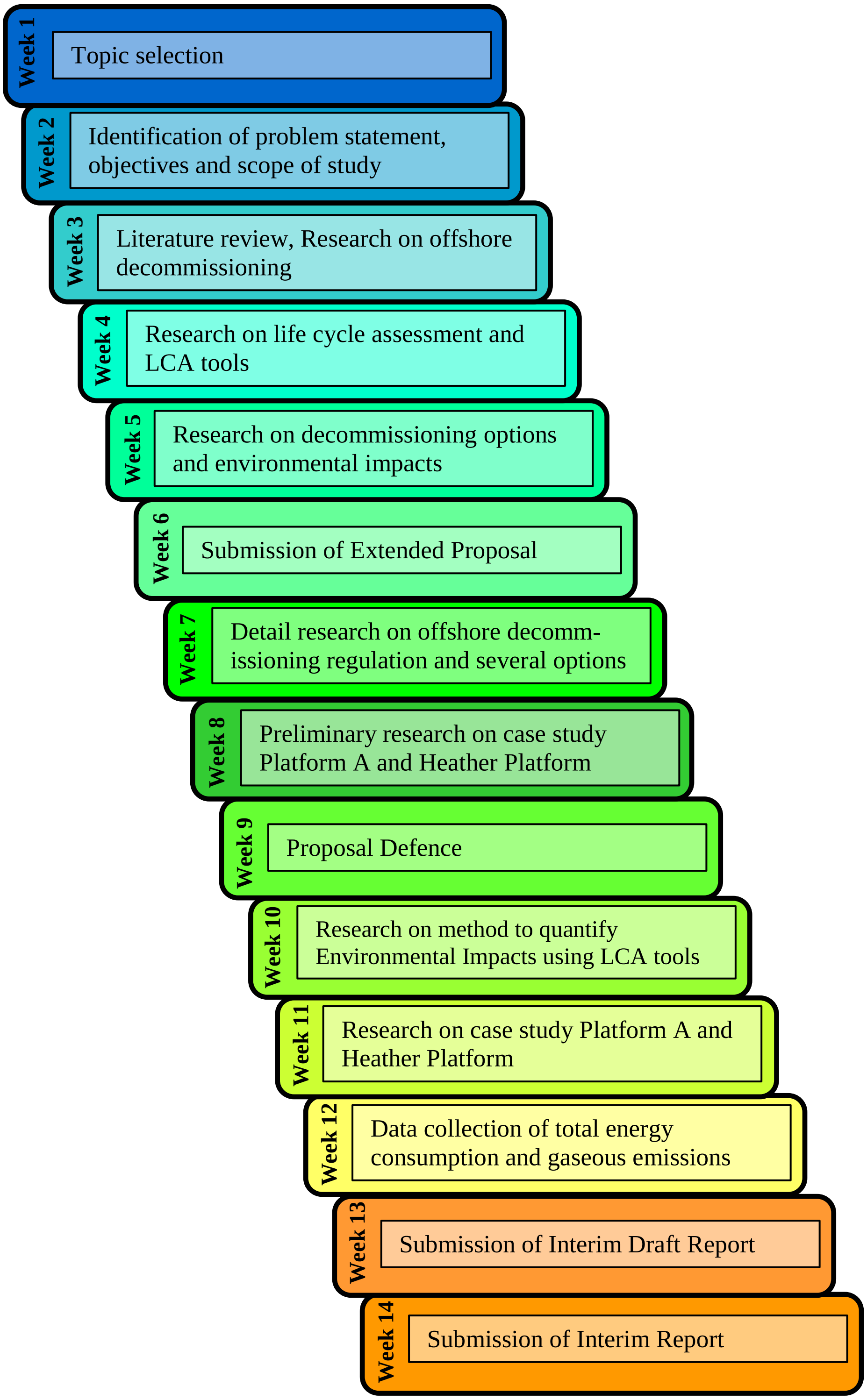


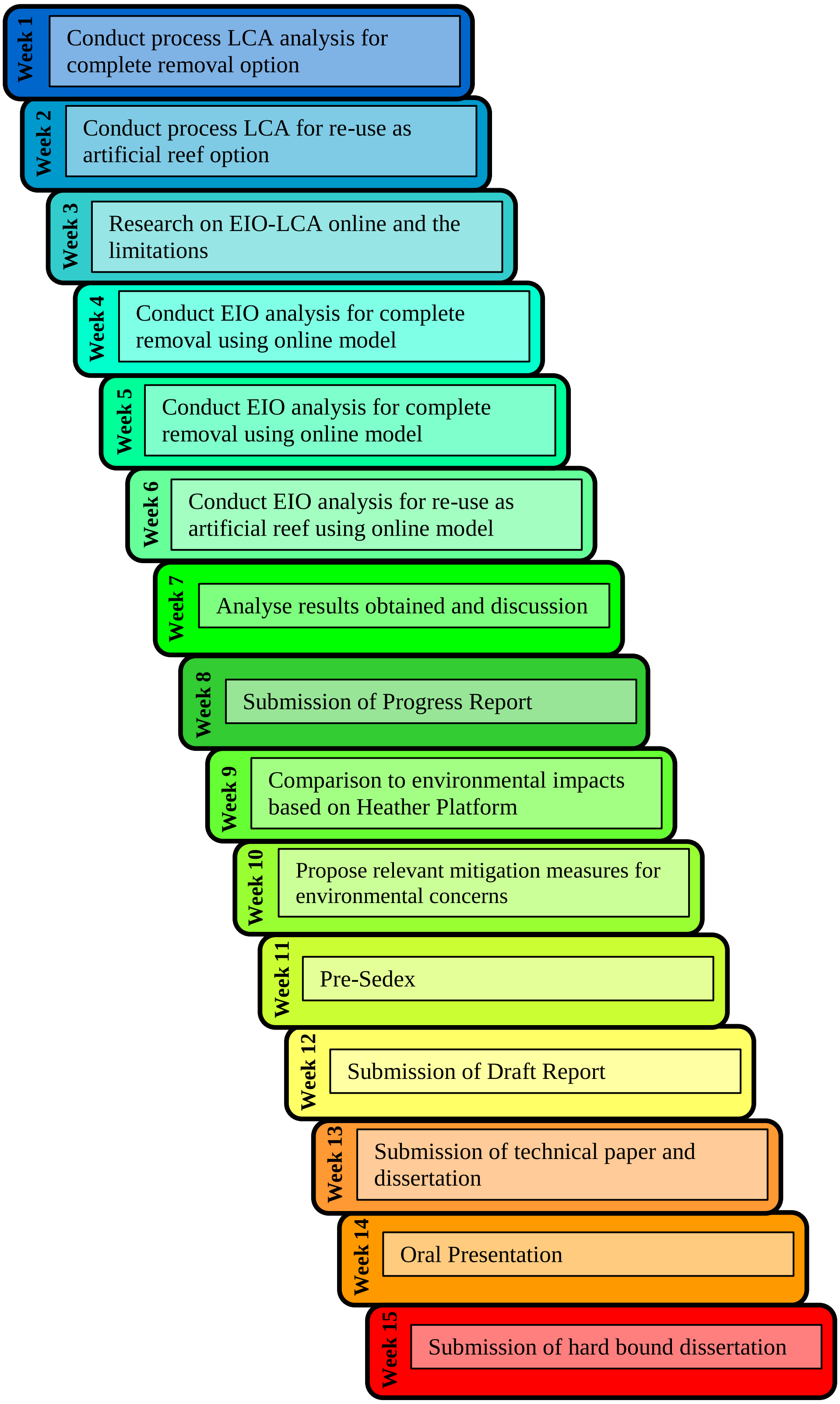
Figure 13: Project activities involved in this study

3.4 KEY MILESTONES

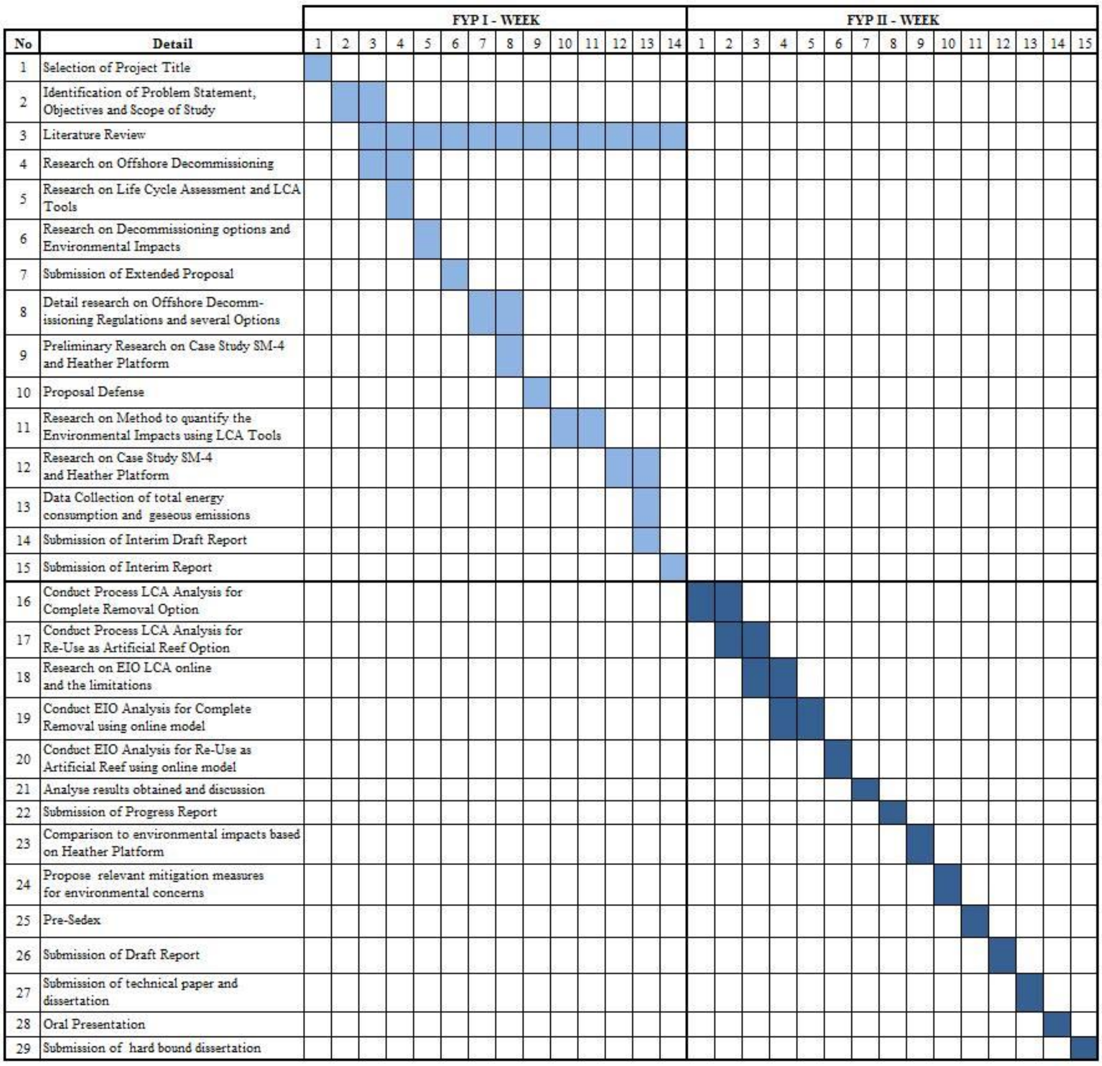
The planned schedule for Final Year Project I is as follows:



The planned schedule for Final Year Project II is as follows:



3.5 GANTT CHART



3.6 LCA METHODOLGY

The LCA methodology applied in this study includes four stages based on the ISO standard, described previously in the literature review.

3.6.1 PROCESS BASED LCA ANALYSIS

It has to be taken into account that the author set some assumptions and boundaries for this study due to limited available data and to adapt to the LCA analysis conducted for the decommissioning process of Heather Platform. The data used for process based LCA are retrieved from the published BPEO Study for Platform A and several documentations of the decommissioning process. The conversion factors are obtained from a research work published in 1997 due to limited information available, particularly gaseous emissions associated with decommissioning of offshore structures. However, the unit conversion factors used in the paper published by Side, Kerr and Gamblin (1997) are checked with the recent published rate (Department of Energy & Climate Change, 2013) and confirmed that the differences is not significant. For instance, the carbon dioxide emission conversion factor due to the use of aviation fuel just differs by 5 % compared to the recent factor according to the Annual European Union greenhouse gas inventory 1990-2011 and inventory report 2013.

Although this data is published by European Departments, primary suitable for the UK and the North Sea, those conversion factors are applied in this study in order to be able to compare the obtained amounts of gaseous emissions and total energy consumption with these of decommissioning Heather Platform.

The unit conversion factors for energy consumption and gaseous emissions related to steel production, steel recycling and fuel consumption, including their respective references, are provided in the Appendices. Furthermore, the used haulage constants such as travel distances and also fuel consumption factors for on- and offshore transport as well as for vessel utilisation and dismantling operations are attached in the appendix.

Data variables involved due to assessing two decommissioning options, complete removal and conversion to an artificial reef which influence the total energy consumption and gaseous emissions are developed and can be also found in the appendix.

3.6.2 EIO-LCA ANALYSIS

The data incorporated into the EIO-LCA model is compiled from surveys and forms submitted by industries to the government for national statistical purposes, which leads to uncertainties in sampling and incomplete data or estimates. The data implemented in the online model is based on the US 2002 Benchmark model, where 428 industry sectors where each of them represents a collection of several industry types, are involved. The data associated with each model are representative of the year of the model including the economic input-output matrix and the environmental data. Thus, in using the model to replicate current conditions, it has to be taken into account that the changes in data could vary widely over the time. Since the data applied in the EIO model is based on the year 2002 the model documentation was observed and it was discovered that the Green Design Institute revised the model with latest economic-input-output coefficients in 2009. Hence the results would be valid.

The EIO-LCA method is a linear model and represents impacts through the production of output by the sector based on an economic value (U.S. dollar values). Most of the EIO models which form the basis for the EIO-LCA models represent the producer priced model which has the boundaries of "cradle to gate". This model estimates impacts from resource extraction all the way up to final assembly of the product as it leads to the factory gate (not including delivery). The appropriate economic input into the model in this case is the total price the producer receives for goods and services with taxes and minus subsidies or the costs for buying materials, running facilities and labour costs. Apart from that, a purchaser priced model has the boundaries of "cradle to consumer”, which includes from resource extraction all the way up to purchase of the product. The appropriate economic input is the producer price with the transportation costs of shipping the product to the point of sale and a profit margin. For the present study the purchase priced model is chosen, as the removed materials are returned onshore for recycling (Green Design Institute).

By applying the EIO model, the total energy consumption and gaseous emissions associated with the decommissioning of Platform A could be determined.

3.6.3 STAGE 1: GOAL AND SCOPE DEFINITION

According to the ISO Standards, the goal of the LCA has to be defined firmly with the reasons, field of application and groups involved. For this assessment, the goal is conform to the objectives of this study, which require the identification and quantification of the environmental impacts associated with the decommissioning of fixed offshore platforms in Malaysia, and the proposal of relevant mitigation measures for environmental concerns arising with this process.

The scope of this study is limited to two decommissioning options: the complete removal and re-use as an artificial reef. Platform A, a small platform located in the shallow water of the South China Sea offshore Sabah is selected as the case study for this project.

The following boundaries are set according to the assessment of total energy consumption and gaseous emissions for the decommissioning of Heather Platform published by Side, Kerr & Gablin (1997) to ensure the consistency in data evaluation, that no energy is being counted twice and to be able to compare these results with them for decommissioning Platform A (Ngu Pei Jia, 2013).

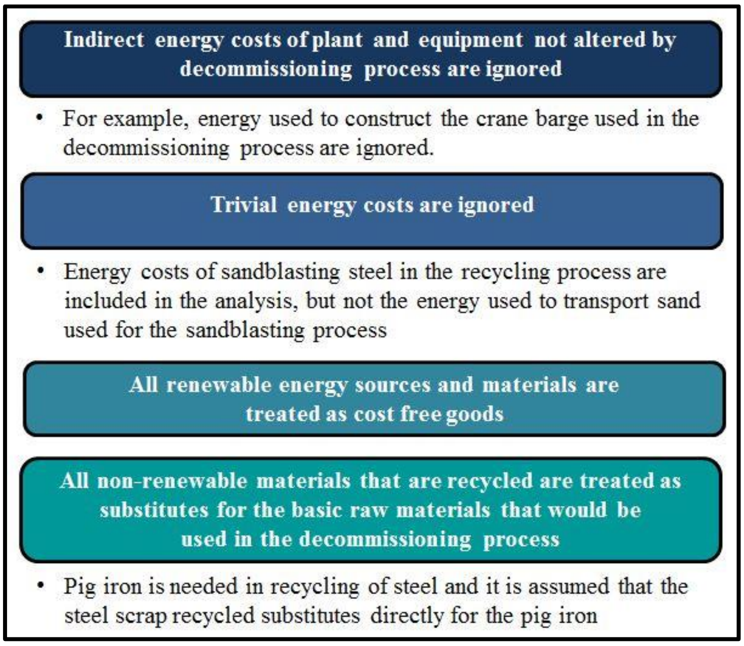


Figure 14: Defined boundaries for consistency in data evaluation

3.6.4 STAGE 2: LIFE CYCLE INVENTORY FOR PROCESS BASED LCA

The Life Cycle Inventory (LCI) analysis includes the data collection and calculation to estimate relevant inputs and outputs of the system (Poremski, 1998). For offshore decommissioning the input is the energy consumption, whereas the outputs are the produced gaseous emissions. The four inventory parameters concerned in this paper are Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x) and Sulphur Dioxide (SO_2) and Equivalent Carbon Dioxide due to their significance in the contribution for emissions associated with offshore installations decommissioning.

The LCA methods used in this project are process based- and EIO-LCA. For the LCI implemented in process based method, used to estimate the total energy consumption and gaseous emissions associated with decommissioning of Platform A, the data were obtained from a paper published by Side et al. (1997), the BPEO Study for Platform A and from documentation documents about the decommissioning process.

For the ease of data evaluation in process based LCA, the decommissioning process for Platform A is divided into several discrete aspects, consisting of:

Marine vessel utilisation	• Product of vessel utilisation and corresponding fuel consumption
Platform Dismantling	• Removed platform materials, fuel consumption for dismantling operations
Platform Material Recycling	• Product of recycling materials
Platform Materials left at Sea	• Product of materials left at sea (for re-use as artificial reef)
Transportation Onshore	• Removed materials of dismantling operations: transportation of materials for recycling and disposal onshore

It should be attended that the Well Abandonment of Platform A is not considered in this study as it was done before. Hence, it is focused on the decommissioning of the structural components of Platform A; the topside, boat landing and jacket. Further, for each of the aspects boundaries are set to define the scope for process based LCI In Table 5 it is pointed out what is taken into consideration in order to get an appropriate result for the total energy consumption and gaseous emissions produced during decommissioning Platform A, but otherwise to be able to get along with limited information.

Table 5: Assumptions for process based LCA

Decommissioning Aspect	Assumptions for complete removal	Assumptions for conversion to an artificial reef
Marine Vessel Utilisation (Figures which show the vessel types and the duration and kind of use are attached in the Appendices)	• Used marine vessels: ○ Work Barge ○ 2 AHT (WB) ○ Dumb Barge ○ 2 AHT (DB) ○ Support Vessel ○ Supply Boat • Distinguishing of in port, in transit, working and waiting on weather (WOW) • Calculation of fuel consumption in port and working per day • Calculation of fuel consumption in transit per mile • Travel distance from Port Labuan to Platform A site • Travel distance to Pasir Gudang, Johor for recycling	• Used marine vessels: ○ Work Barge ○ 2 AHT (WB) ○ Dumb Barge ○ 2 AHT (DB) ○ Support Vessel ○ Supply Boat • Distinguishing of in port, in transit, working and waiting on weather • Calculation of fuel consumption in port and working per day • Calculation of fuel consumption in transit per mile • Travel distance from Port Labuan to Platform A site • Travel distance to Pasir Gudang, Johor for recycling • Travel distance to artificial reef site
Platform Dismantling	• Cutting methods applied: ○ Oxy-Acetylene Cutting ○ Abrasive Water Jet Cutting ○ Diamond Wire Cutting	• Cutting methods applied: ○ Oxy-Acetylene Cutting ○ Abrasive Water Jet Cutting ○ Diamond Wire Cutting

	• Cutting into sections is not considered (insignificant) • Propane consumption is constant for each cutting method • Energy consumption of dismantling timber and miscellaneous materials are not considered • Dismantling of boat landing, topside, jacket and conductor • Removal of marine growth	• Cutting into sections is not considered (insignificant) • Propane consumption is constant for each cutting method • Energy consumption of dismantling timber and miscellaneous materials are not considered • Dismantling of topside and conductor • No removal of marine growth
Platform Materials Recycling	• Recycling of steel from boat landing, topside, jacket and conductor	• Recycling of steel from topside and conductor
Platform Materials left at Sea	• Mudmat (timber) is not considered • Nothing is left at sea	• Mudmat (timber) is not considered • Marine growth is not removed and left at sea but not considered • Jacket and boat landing are towed to artificial reef site → Replaced with steel produced from ore
Transportation Onshore	• Fabrication Yard (Pasir Gudang, Johor) • Scrap Dealer (Pasir Gudang, Johor) • Disposal Site (Pasir Gudang, Johor)	• Fabrication Yard (Pasir Gudang, Johor) • Scrap Dealer (Pasir Gudang, Johor) • Disposal Site (Pasir Gudang, Johor)

3.6.5 STAGE 2: LIFE CYCLE INVENTORY FOR EIO-LCA

The cost input data to perform LCA analysis, using the EIO online model, was retrieved from a cost estimation for complete removal for the used case study, the offshore structure Platform A located in the South China Sea, from the PETRONAS Petroleum Management Unit. The estimated cost for decommissioning Platform A is total up to RM 27,187,304.25, which is US$ 8,860,386.14.

As for the conversion to an artificial reef there is no suitable cost information available, they are assumed based on the comparison between the costs of complete removal and the conversion to an artificial reef calculated for three Offshore Structures in the Gulf of Mexico. By comparing the costs obtained from a paper published by Twatchman Snyder & Byrd, Inc. (2000) for decommissioning the Platform Hidalgo, Gail and Harmony, the average difference between the costs for the different decommissioning options could be taken, which results in 35 %. Hence, the costs for the conversion to an artificial reef of Platform A are assumed to be RM 9,515,556.49, thus US$ 3,101,135.15.

As the cost data was obtained in Ringgit Malaysia, the author converted the cost to US Dollar in order to be able to use the value in the EIO model. Although the currency rate fluctuates every day, the result might not be affected much, as the fluctuation rate is insignificant compared to the amount of decommissioning costs.

For EIO-LCA, the EIO online model from www.eiolca.net, where a database is already implemented as stated before, is conducted to assess the total energy consumption and gaseous emissions associated with offshore decommissioning. The US 2002 Purchaser Price Model is chosen, Mining and Utilities as Broad Sector Group and Support activities for oil and gas operations as detailed industry sector selected. This U.S. industry involves support activities on a contract or fee basis for oil and gas operations (except site preparation and related construction activities). Services included are exploration (except geophysical surveying and mapping); excavating slush pits and cellars; well surveying; running, cutting, and pulling casings, tubes and rods; cementing wells; shooting wells; perforating well casings; acidizing and chemically treating wells; and cleaning out, bailing, and swabbing wells (Green Design Institute). The amount of economic activity is assumed to be one million US Dollar.

3.6.6 STAGE 3: LIFE CYCLE IMPACT ASSESSMENT

Life Cycle Impact Assessment involves the evaluation of the significance of potential environmental impacts based on the results obtained by performing the previous stage. After the inventory data is classified into their respective impact category the data is modelled within those categories and finally prioritised and weighted. The impact categories applicable in this conducted LCA are global warming (CO_2 and Equivalent CO_2) and acidification (SO_2 and NO_x) according to the Scientific Applications International Corporation (2006).

3.6.7 STAGE 4 LIFE CYCLE INTERPRETATION

The Life Cycle Interpretation includes the combination and interpretation of the findings from the inventory analysis and impact assessment. During the final stage of this study, the decommissioning activity, which has the greatest contribution to total energy consumption and gaseous emissions, may be identified. The more appropriate decommissioning option could be suggested based on the results. Furthermore the quantitative outcomes provided by the different LCA tools can be compared with each other and as well with the findings based on decommissioning of Heather Platform. Additionally relevant mitigation measures for environmental concerns, that arises in connection with the decommissioning of fixed offshore platforms could be suggested and recommendations be given.

3.7 SUMMARY

In this chapter, the methodology used in this research, was presented. The main problem and the objectives were taken up again in the beginning of this chapter. The research methodology as well as project activities, key milestones and the schedule for the study were stated. In addition, detailed steps required and established for LCA analysis including assumptions and boundaries set, were outlined in the previous part of this chapter. In the following chapter, the results from process based- and EIO-LCA will be presented in table and graph format and further explained, interpreted and discussed. Afterwards, recommendations regarding decommissioning of offshore structures and LCA analysis will be proposed.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter will comprise the results of process based- and EIO-LCA. The results will be further explained, interpreted and discussed. Subsequently, recommendations regarding possible mitigation measures for environmental concerns arising with the decommissioning of offshore structures, focussing on marine vessel utilisation will be suggested.

4.2 RESULTS AND DISCUSSION

4.2.1 PROCESS BASED LCA

The data applied to conduct process based LCA were retrieved from a published paper by Side et al. (1997) describing the estimation of energy consumption and gaseous emissions associated with the decommissioning of Heather Platform, the BPEO Study for Platform A as well as several documentations of the decommissioning process. The detailed input data including unit conversion factors, constants, distances, average fuel consumptions and executed calculations are attached in the Appendices. Total energy consumption and gaseous emissions were assigned to several decommissioning aspects for the ease of evaluation and to be able to identify the aspect with the greatest contribution.
Table 6 indicates the quantitative results for total energy consumption and gaseous emissions, obtained by process based LCA using EXCEL Software for both decommissioning options of Platform A; complete removal and conversion to an artificial reef.

The detailed results for each aspect are also shown in Appendix L.

Table 6: Results and percentage difference between complete removal and conversion to artificial reef of Platform A in terms of energy consumption and gaseous emissions using process based LCA

Variable	Complete Removal	Conversion to an Artificial Reef	Difference [%]
Energy Consumption [GJ]	37,105	38,151	2.74
SO_2 Emissions [kg]	36,409	36,802	1.07
NO_x Emissions [kg]	36,372	36,759	1.05
CO_2 Emissions [kg]	2,535,263	2,649,652	4.32
Equivalent CO_2 Emissions [kg]	1,539,531	1,555,829	1.05
Overall CO_2 Emissions [kg]	4,074,794	4,205,481	3.11

Based on the results shown in Table 6 and as shown in Figure 14, it can be concluded, that the conversion to an Artificial Rees consumes more energy and produces more gaseous emissions than complete removal. However, the values for total energy consumption and gaseous emissions produced during complete removal and conversion to an artificial reef do not vary widely (between 1.05 and 4.32 %).

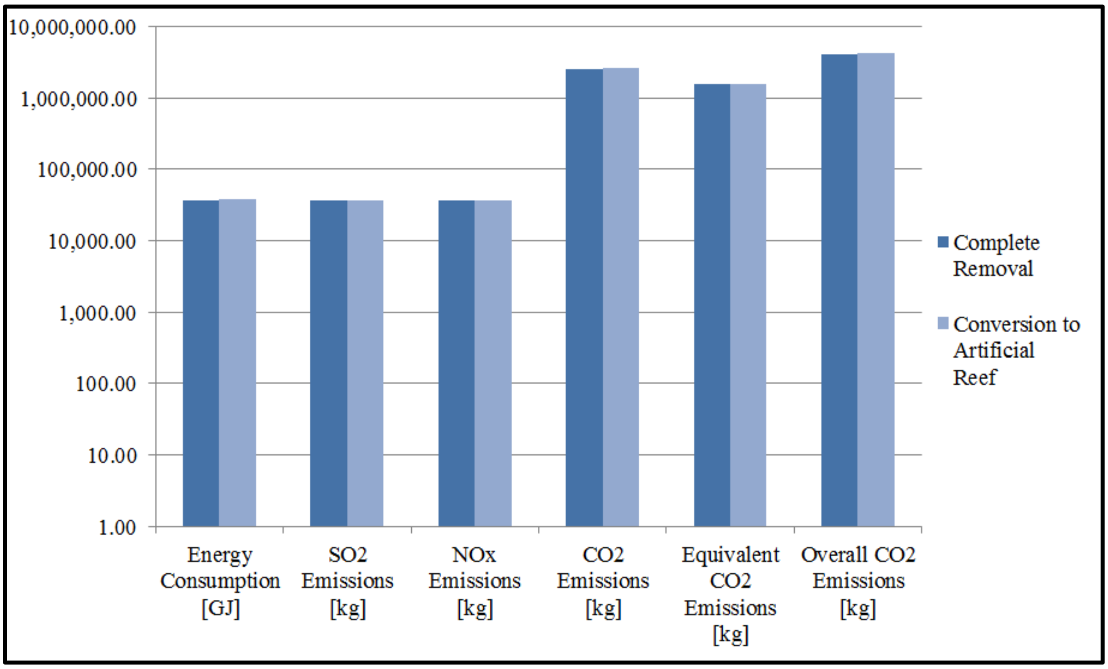


Figure 15: Comparison between total energy consumption and gaseous emissions depending on decommissioning option for Platform A

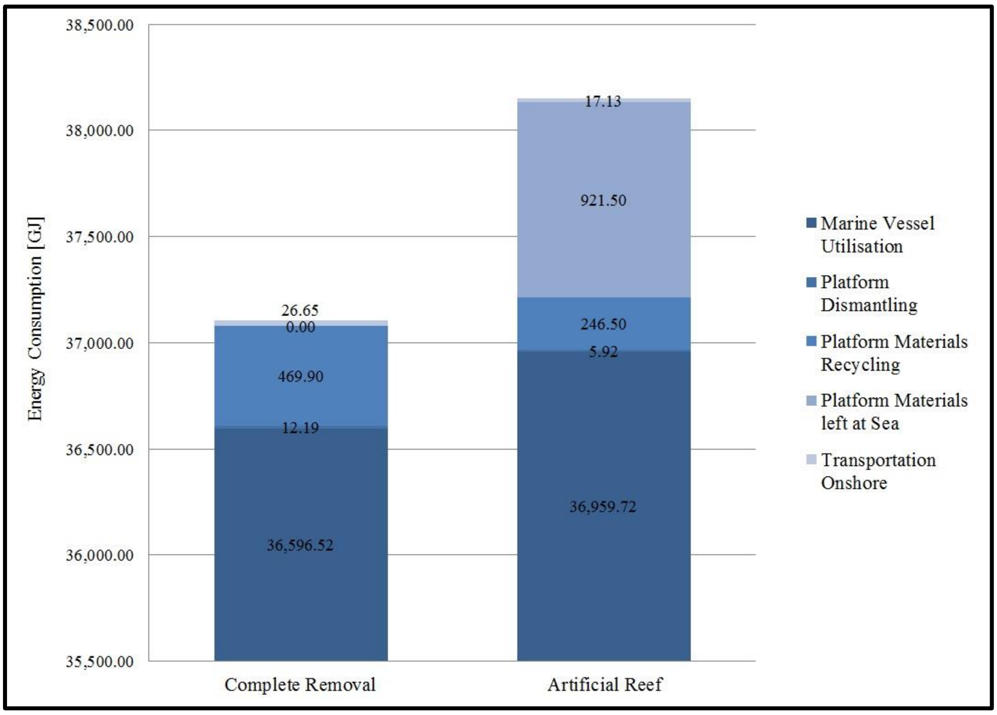


Figure 16: Breakdown of energy consumption [GJ] with respective decommissioning activities for complete removal and conversion to artificial reef for Platform A

As illustrated in Figure 15, it becomes clear, that the energy consumption in the case of conversion to an artificial reef is higher (2.74 %) than in performing complete removal. The higher energy consumption arises since the amount of steel which is left at sea to create the artificial reef is replaced by steel production from ore, which requires big amounts of energy. Furthermore it is also considered, that the topside is brought onshore for recycling, which results in a greater marine vessel utilisation than in the case of complete removal.

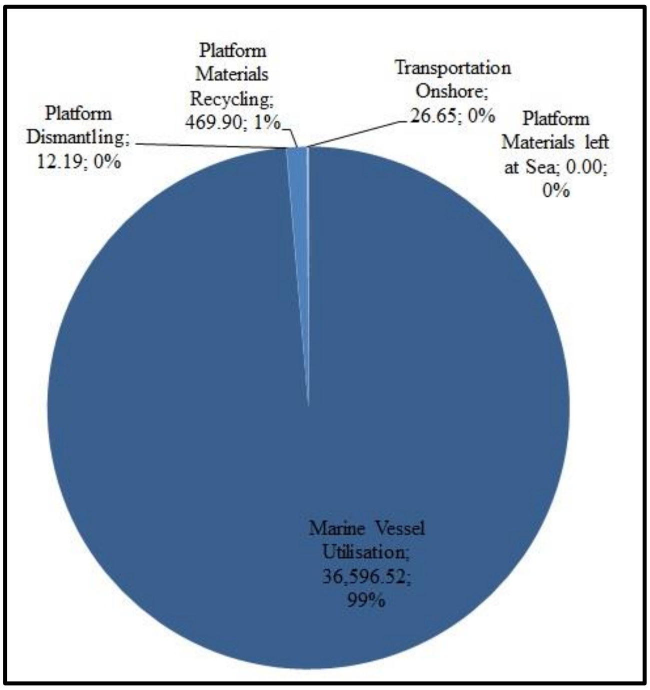


Figure 17: Energy consumption [GJ] of complete removal depending on decommissioning activities for Platform A

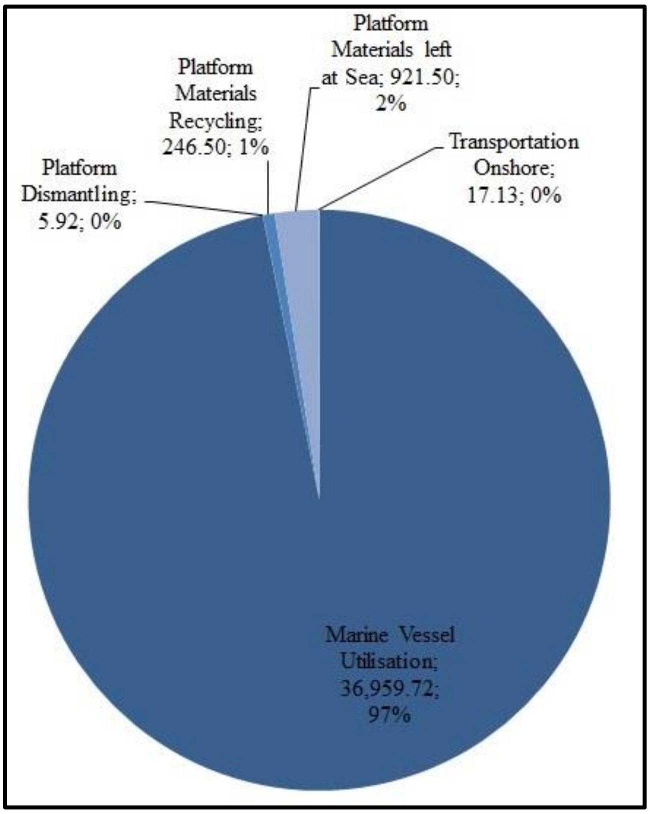


Figure 18: Energy consumption [GJ] of conversion to artificial reef depending on decommissioning activities for Platform A

The pie charts in Figures 16 and 17 exhibit, that the marine vessel utilisation is the largest energy consuming activity during complete removal (99 %) and conversion to an artificial reef (97 %). The energy consumption due to platform dismantling, recycling and transport onshore are proportional insignificant. Just the materials left at sea in case of conversion to an artificial reef contribute slightly due to the consideration as steel produced from ore as mentioned before. It indicates the energy wasted as the material is not recycled.

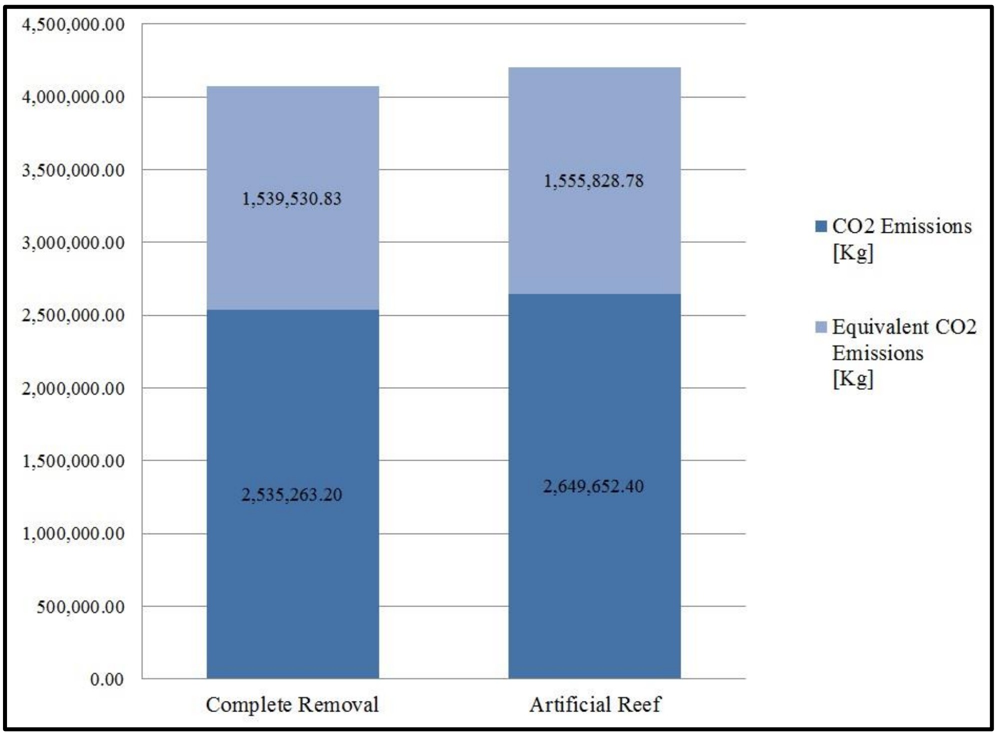


Figure 19: Overall CO_2 emissions [kg] depending on decommissioning option for Platform A

The CO_2 and Equivalent CO_2 emissions are designated as the main factors for global warming resulting in an increase of the sea level at heat waves. In order to investigate which decommissioning option contributes more to global warming it is focussed on the overall CO_2 emissions. As seen in Figure 18 it is evident, that the amount of overall CO_2 emissions is similar regarding the two different decommissioning options with a percentage difference of 3.11 %. However, it is illustrated, that conversion to an artificial reef produces more CO_2 emissions with 4.32 % more compared to complete removal. The greater production of those emissions is traceable to the greater amount of fuel by the marine vessels used for transport of the jacket and boat landing to the artificial reef site as well as the topside onshore for recycling.

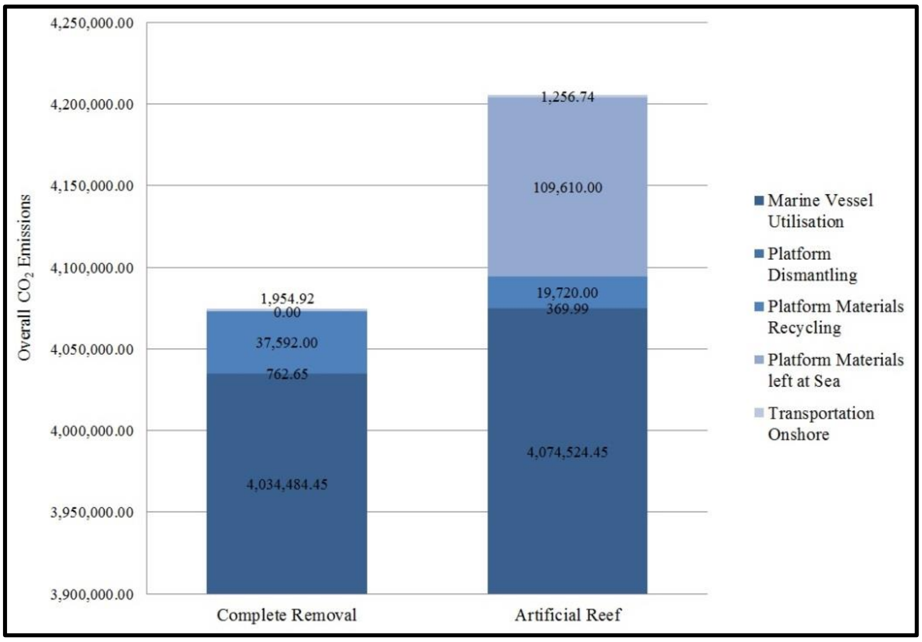


Figure 20: Breakdown of overall CO_2 emissions [kg] with respective decommissioning activities for complete removal and conversion to artificial reef for Platform A

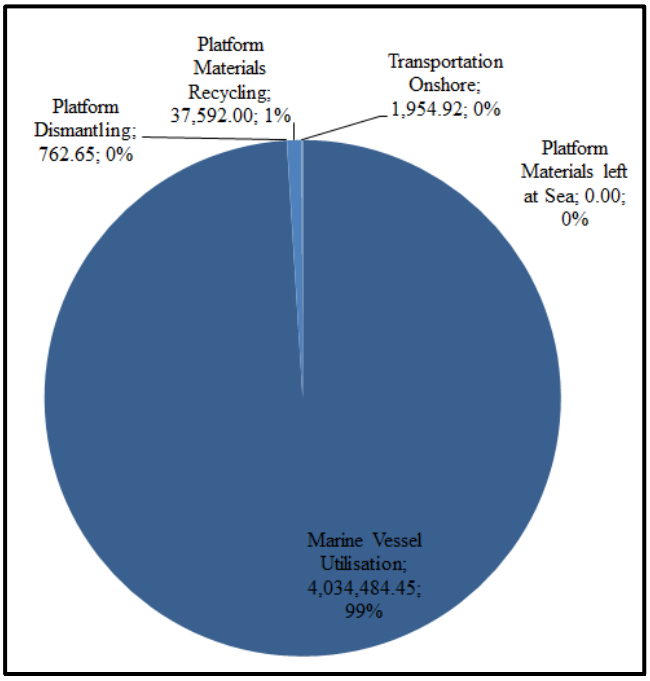


Figure 21: Overall CO_2 emissions [kg] of complete removal depending on decommissioning activities for Platform A

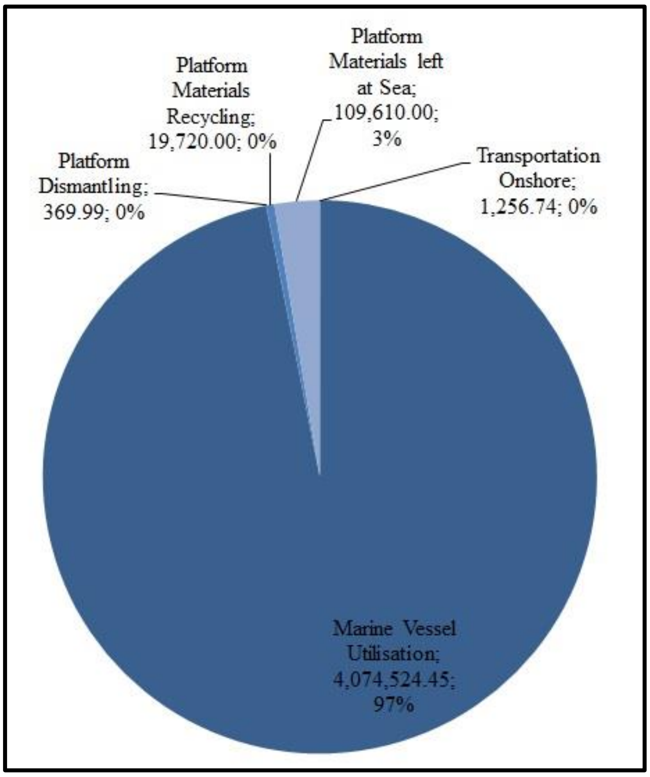


Figure 22: Overall CO_2 emissions [kg] of conversion to artificial reef depending on decommissioning activities for Platform A

From Figure 19, 20 and 21, equal to the total energy consumption, it can be observed that the greatest contribution to the overall CO_2 emission for complete removal and for conversion to an artificial reef with the percentage of 99 % and 97 % respectively, is the marine vessel utilisation. The CO_2 emissions due to platform dismantling, recycling and transport onshore are here as well proportional insignificant. Just the materials left at sea in case of conversion to an artificial reef contribute slightly due to the consideration as steel produced from ore as mentioned before. As stated before, this indicates the energy wasted as the material is not recycled.

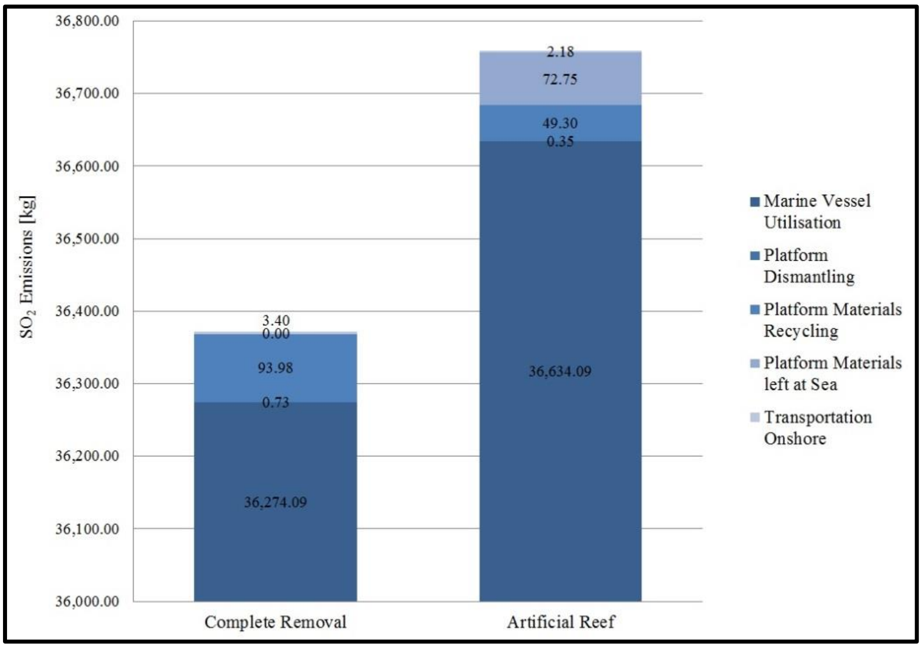


Figure 23: Breakdown of SO_2 emissions [kg] with respective decommissioning activities for complete removal and conversion to artificial reef for Platform A

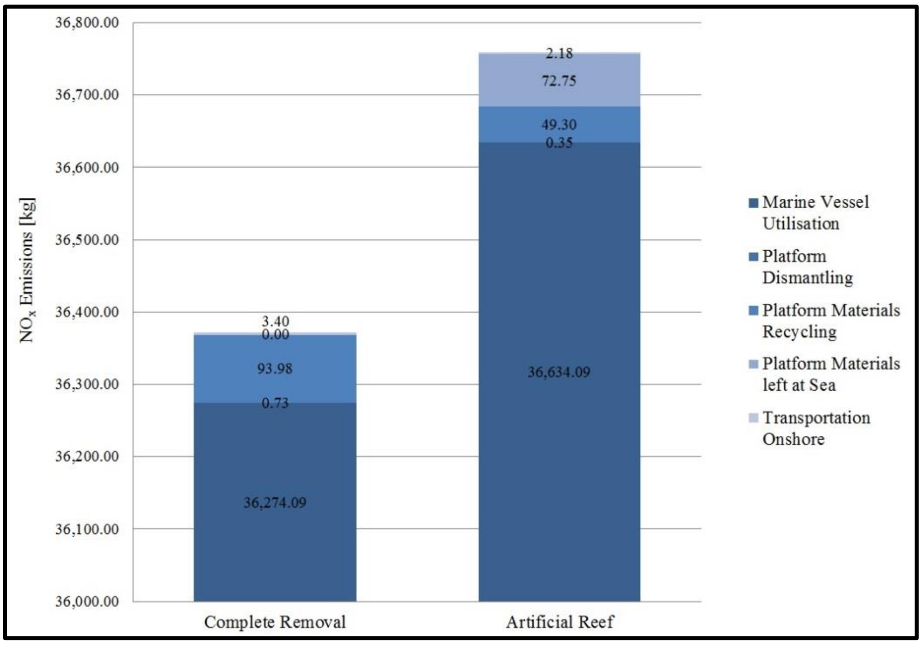


Figure 24: Breakdown of NO_x emissions [kg] with respective decommissioning activities for complete removal and conversion to artificial reef for Platform A

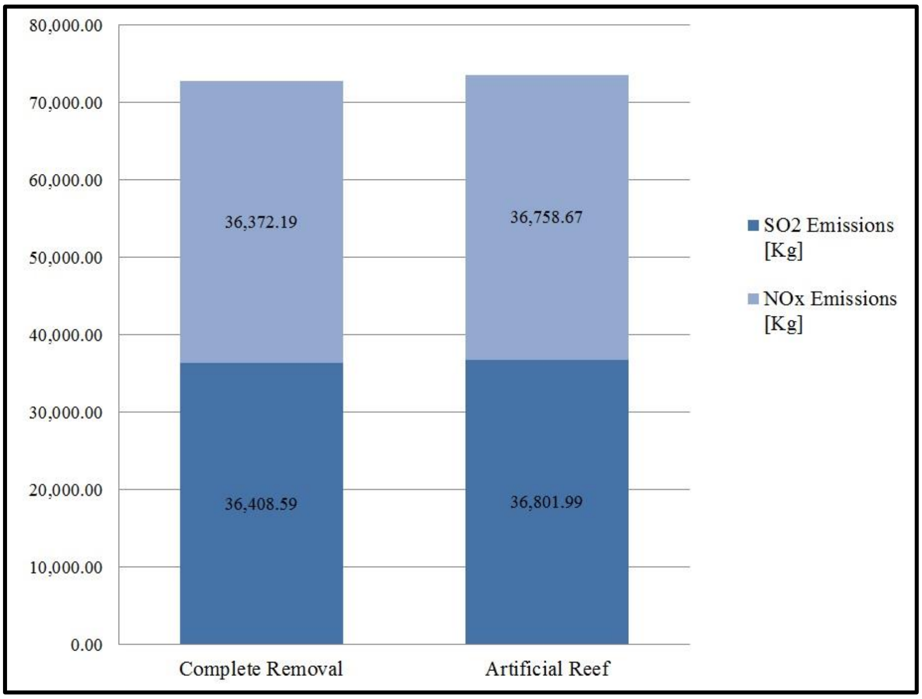


Figure 25: SO_2 and NO_x emissions [kg] depending on decommissioning option for Platform A

SO_2 and NO_x are the main culprits for acid rain which is dangerous to human's health and harms the agriculture and buildings. As shown in Figure 22, 23 and 24, the amount of SO_2 and NO_x emissions released by complete removal and conversion to an artificial reef are quite similar with about 1 % difference. The activity which contributes the most to those emissions is marine vessel utilisation followed by platform material recycling in case of complete removal. On the other hand the conversion of Platform A to an artificial reef produces less SO_2 and NO_x regarding the material recycling, but overall more emissions due to greater usage of marine vessels and the emissions produced during the amount of steel produced which replaces the amount of steel left at sea.

Based on the results obtained from process based LCA using EXCEL Software, it is evident that marine vessel utilisation is the major factor for the energy consumption and the quantity of CO_2, NO_x and SO_2 emissions followed by far by material recycling and the steel production considered for the amount of steel which is left at sea in order to create an artificial reef. From this point it can be concluded, that marine vessel utilisation should be reduced in order to minimise the environmental impacts offshore decommissioning. Marine vessels consume great amounts of fuel (energy) and release a large amount of the greenhouse gas CO_2 and also harmful gases SO_2 and NO_x.

From these results, it can be summarised that the conversion to an artificial reef has a greater energy consumption and produces more gaseous emissions. This contradicts initial expectations as this option is considered as more environmental friendly and beneficial for the marine environment. The higher amount of vessel utilisation and greater travel distances due to material transport both to the artificial reef site and to the selected fabrication yard for further recycling purposes leads to the higher energy consumption and discharge of gaseous emissions compared to complete removal. Although the complete removal option provides the greater amount of steel which is recovered for recycling purposes, it does not compensate the marine vessel utilisation and the steel production required due to materials left at sea in case of the conversion to an artificial reef. Otherwise the results received for complete removal and the conversion to an artificial reef correspond in the identification of the decommissioning activity which contributes most to the investigated issues which is in both cases the vessel utilisation.

In conclusion, for decommissioning Platform A the re-use as an artificial reef is not an appropriate and beneficial option due to large travel distances disproportionate to the size of the platform. Actually, Platform A was decommissioned in a group with another offshore installation. In further studies, it could be examined if the result would be different in terms of total energy consumption and gaseous emissions, if the ratio of the amount of the removed material to the travel distances is smaller.

4.2.2 EIO-LCA

The data applied to perform EIO-LCA were obtained from a cost estimation compiled by PETRONAS Petroleum Management Unit for complete removal of Platform A. The costs for conversion to an artificial reef were assumed as a percentage (35 %) of this determined sum as stated before. The total energy consumption and gaseous emissions were calculated by referring to the standard unit economic value of one million US dollar implemented in the purchaser price model for support activities for oil and gas operations provided by the Green Design Institute's online tool on www.eiolca.net. The input data and also the total energy consumption and gaseous emissions for the standard unit are attached in the Appendices.

Table 7: Results of complete removal and conversion to artificial reef of Platform A in terms of energy consumption and gaseous emissions using EIO-LCA

Variable	Standard Unit (1 million US Dollar)	Complete Removal (8.86 million US Dollar)	Conversion to an Artificial Reef (3.10 million US Dollar)
Total Energy Consumption [GJ]	7790	69,022.41	24,157.84
SO_2 Emissions [kg]	1890	16,746.13	5,861.15
NO_x Emissions [kg]	6330	56,086.24	19,630.19
Overall CO_2 Emissions [kg]	650000	5,759,250.99	2,015,737.85

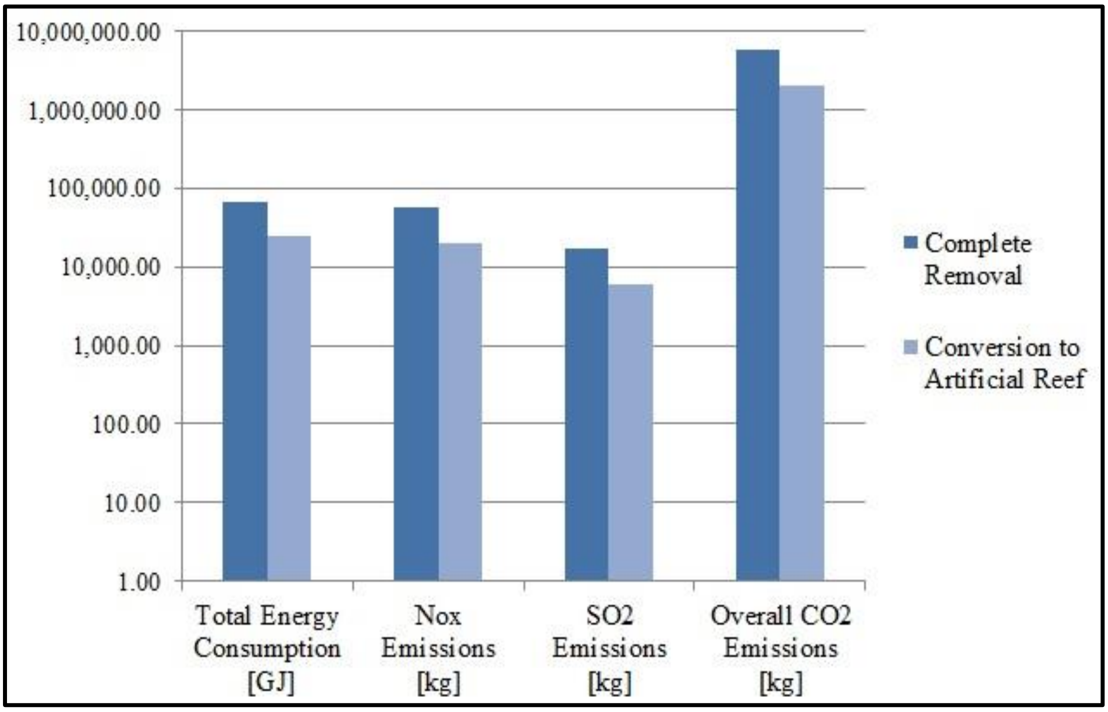


Figure 26: Comparison between total energy consumption and gaseous emissions depending on decommissioning option for Platform A

On the basis of the obtained results and as consequence of the applied calculation model with dependence on the respective option costs, it is straightforward that complete removal requires about 65 % more energy and releases about 65 % more harmful gaseous emissions. In contrast to process based LCA, by using EIO-LCA analysis, conversion to an artificial reef is the more appropriate decommissioning option in terms of energy consumption and gaseous emissions due to lower cost assumed based on empirical estimations which consider the re-use as an artificial reef as more cost-effective.

4.2.3 COMPARISON PROCESS BASED LCA AND EIO-LCA

In the present study, by conducting the two different LCA tools process based method and EIO method, the outcome is totally different. Using process based LCA complete removal of Platform A is the better decommissioning option in terms of energy consumption and gaseous emissions. On the other hand by performing EIO-LCA conversion to an artificial reef requires less energy and produces less harmful gaseous emissions. Besides that the difference between the values estimated using the EIO online model are much higher corresponding to the assumed cost difference of 65% between complete removal and conversion to an artificial reef. However, the differences between the numerous results obtained by establishing process based method just vary in the range of 1.05 % and 4.32 %. For this LCA analysis more assumptions were made in terms of vessel utilisation and travel distances due to limited information available.

Table 8: Percentage differences between the results of process based- and EIO-LCA

	Difference [%]	
Variable	**Complete Removal Platform A**	**Conversion to an Artificial Reef Platform A**
Total Energy Consumption [GJ]	46	37
SO_2 Emissions [kg]	54	84
NO_x Emissions [kg]	35	47
Overall CO_2 Emissions [kg]	29	52

From Table 8 it becomes clear, that there are huge differences between the calculated values for energy consumption and gaseous emissions related to the two different decommissioning options. The results vary in the range of 29 % and 54 % in case of complete removal and between 37 % and 84 % for conversion to an artificial reef. Those differences between the tools occur due to the made assumptions for process based- as well as for EIO-LCA analysis. Different input data is required for conducting the two LCA analyses, which are estimated cost for EIO method and for process based method the vessel utilisation, travel distances, conversion factors as well as the quantity of materials for recycling, left at sea and transported onshore. Furthermore, the different perspectives of the tools contribute to the varying numerous outcomes obtained for complete removal and conversion to an artificial reef. Whereas, for EIO method economic values based on experiences and retrieved by industrial surveys are implemented, process based LCA analysis takes the several decommissioning processes into account.

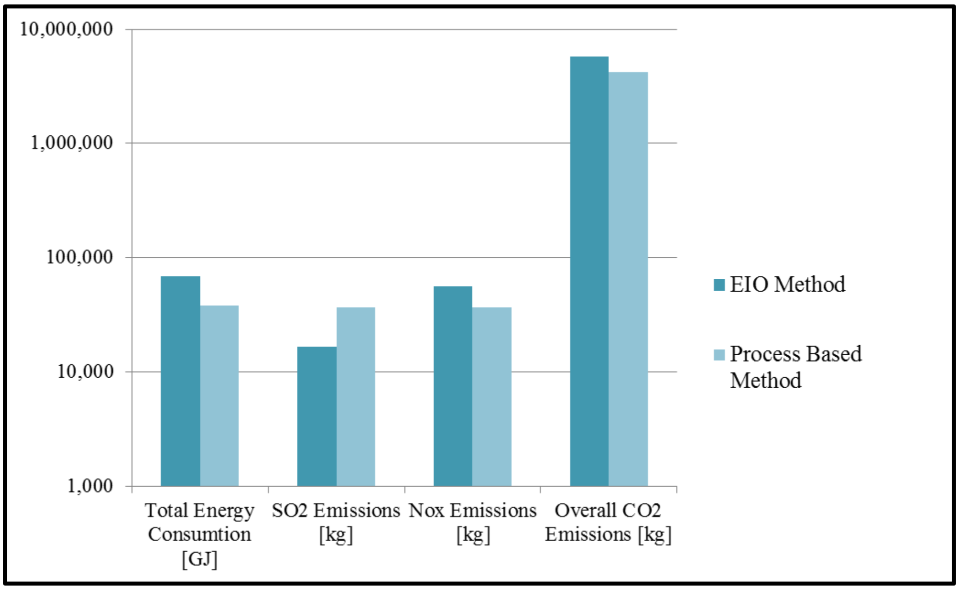


Figure 27: Comparison between the results of process based- and EIO-LCA for complete removal

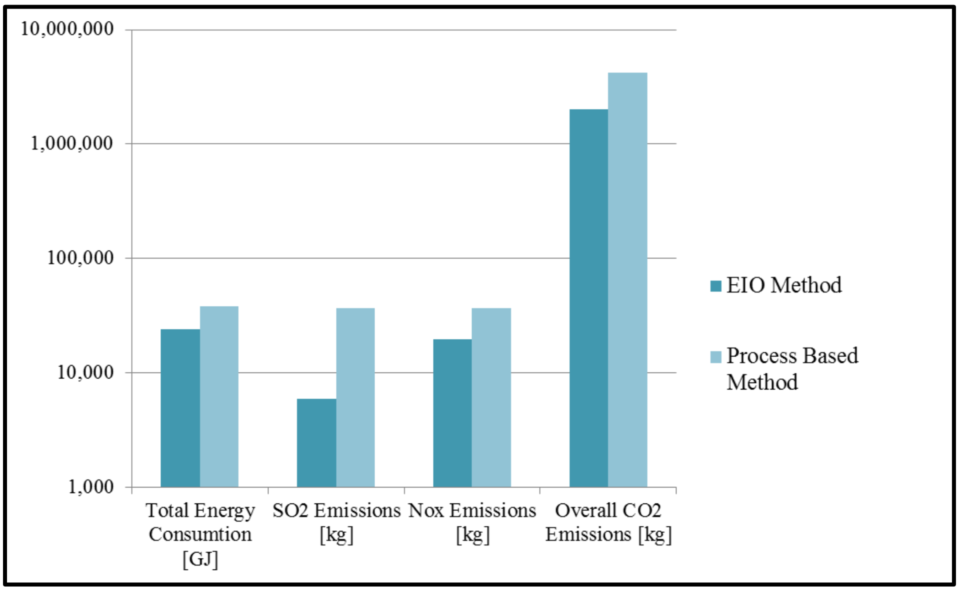


Figure 28: Comparison between the results of process based- and EIO-LCA for conversion to an artificial reef

However, as it can be observed in Figure 26 and 27 that the trend is quite similar. For both considered decommissioning options, the amounts of energy consumption as well as for SO_2 and NO_x emissions are nearly on the same level using each of the

LCA tools. For both analyses, the CO_2 emissions are the major emissions and much higher than the other gaseous emissions. Although the numerous differences are partly huge the observed trend of distribution is similar for the two performed LCA tools.

The detailed calculated numerous and percentage differences are attached in Appendix Q.

4.2.4 COMPARISON PLATFORM A AND HEATHER PLATFORM

Table 9: Comparison of results from process based method for complete removal of Platform A and Heather Platform

	Process Based Method		
Variable	**Complete Removal Platform A**	**Complete Removal Heather Platform**	**Difference [%]**
Energy Consumption [GJ]	37,105	939,479	96.05
SO_2 Emissions [kg]	36,409	631,674	94.24
NO_x Emissions [kg]	36,372	624,318	94.17
CO_2 Emissions [kg]	2,535,263	65,149,362	96.11
Equivalent CO_2 Emissions [kg]	1,539,531	26,301,329	94.15
Overall CO_2 Emissions [kg]	4,074,794	91,450,691	95.54

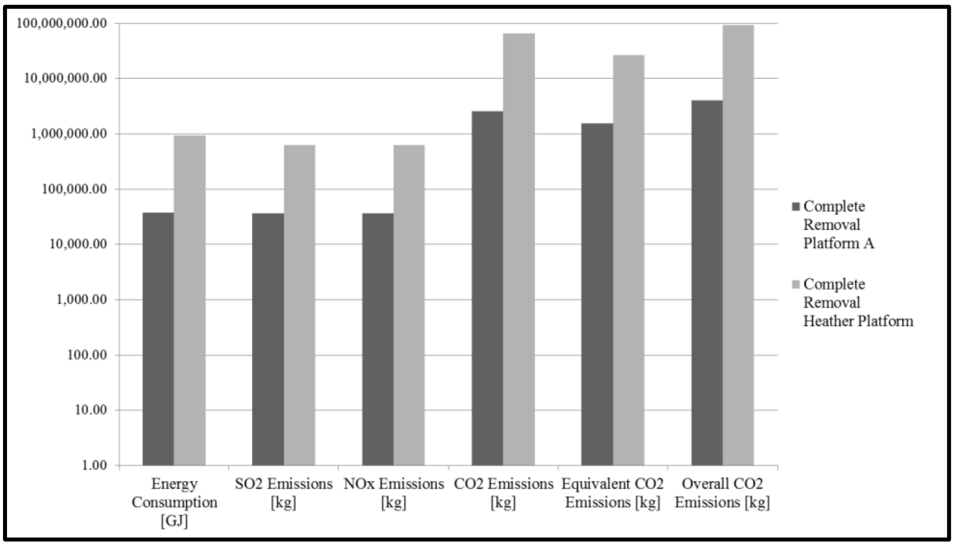


Figure 29: Comparison between total energy consumption and gaseous emissions obtained from process based method depending on complete removal of Platform A and Heather Platform

From the results of energy consumption and gaseous emissions for complete removal of Platform A and Heather Platform respectively, which are presented in Table 9 it becomes clear, that the average percentage difference is about 95 %. This huge difference in results occurs due to great structural differences such as total height, number of modules, usage, the weight of several components and the water depth as well as the location. Hence, for decommissioning of Heather Platform a bigger amount of vessels and cranes with higher capacity, different quantity and type of equipment and more personnel are required which affects the energy consumption and the produced gaseous emissions compared to the much smaller jacket installation Platform A located in shallow water. To state similarities, from Figure 28, a trend can be observed. The values for energy consumption, NO_x and SO_2 emissions vary in a similar range for Platform A and Heather Platform respectively and also the numbers of CO_2 and equivalent CO_2 exhibit in a much higher range for both of the platforms. Although the location, conditions, objectives and challenges of the decommissioning process and the assumptions for the calculations are different the trend of the amount of energy used and emissions produced are comparable.

Table 10: Comparison of results from EIO method for complete removal of Platform A and Heather Platform

	EIO Method			
Variable	**Standard Unit (1 million US Dollar)**	**Complete Removal Platform A (8.86 million US Dollar)**	**Complete Removal Heather Platform (194.63 million US Dollar)**	**Difference [%]**
Total Energy Consumption [GJ]	7790	69,022.41	1,516,167.70	95.45
SO_2 Emissions [kg]	1890	16,746.13	367,850.70	95.45
NO_x Emissions [kg]	6330	56,086.24	1,232,007.90	95.45
Overall CO_2 Emissions [kg]	650000	5,759,250.99	126,509,500.00	95.45

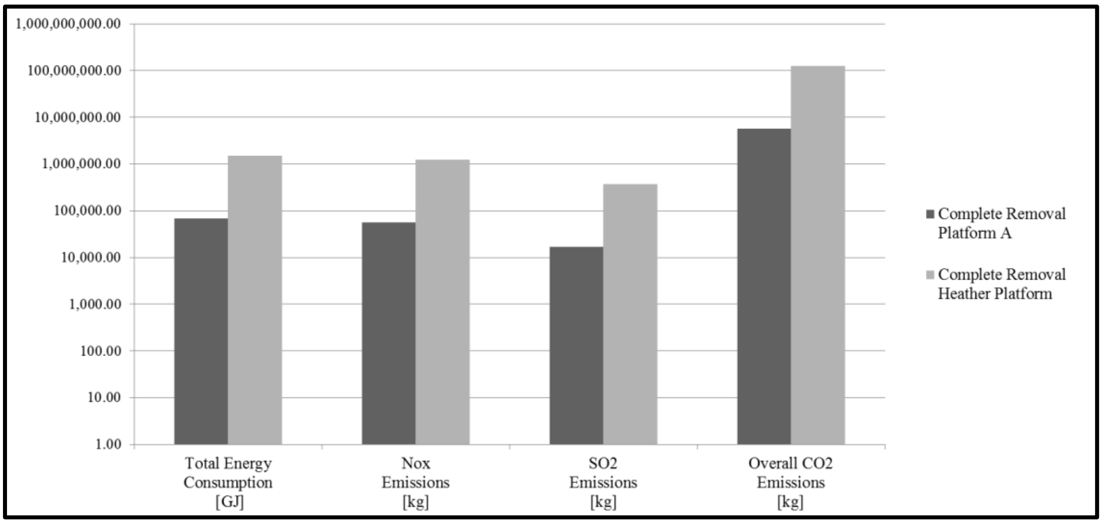


Figure 30: Comparison between total energy consumption and gaseous emissions obtained from EIO method depending on complete removal of Platform A and Heather Platform

The outcome retrieved by conducting EIO method for complete removal of Platform A and Heather Platform is predictable. Due to the difference in cost estimated for the different installations of 95.45 % the percentage differences of total energy consumed and quantity of emissions produced are equal due to input data and the concept of the EIO online model based on the standard unit value for one million US dollar.

Referring to the percentage differences, which are attached in Appendix Q, for energy consumptions and gaseous emissions, calculated by process based and EIO method for Heather Platform, it can be observed that they are similar to the differences for complete removal of Platform A. The results for complete removal of Platform A vary between 29 % and 54 % for the gaseous emissions and with 46 % for energy consumption depending on the conducted LCA tool. Comparable, the percentage differences between the results, gathered from the two performed LCA tools, for the gaseous emissions vary between 28 % and 49 % and for energy consumption with 38 % in case of decommissioning Heather Platform.

Based on the performance of two different LCA tools it becomes clear, that the numerous results for energy consumption and gaseous emissions produced during complete removal obtained, differ about 95 % independent if process based- or EIO-LCA and which input data is used. The assumption, that the environmental impacts calculated for a platform in the North Sea could be converted to values related to the decommissioning of an installation in Malaysia, regardless of the location and conditions given, is obvious. However, it has to be taken into account, that the present study merely assessed the environmental impacts of those two stated structures and that the comparison is done one by one. On this basis it is not possible to issue an accurate statement if this found similarity is overall applicable to estimate the energy consumption and gaseous emissions of future decommissioning projects by using a local unit rate. More information would have been available in order to evaluate apparent differences, boundaries and similarities between decommissioning in Malaysia and the North Sea regarding the energy consumption and gaseous emissions. Besides that, more studies and comparisons based on other offshore structures have to be established to get an accurate result for justification of a comment regarding the coherences and differences of energy consumption and emissions in the different regions.

4.3 MITIGATION MEASURES

The decommissioning activity, which was identified to be the greatest contributor for environmental impacts of offshore decommissioning in terms of energy consumption and gaseous emissions, is the marine vessel utilisation. In the following some suggestions will be proposed to increase the efficiency of marine vessels and to reduce the discharge of harmful gases during the decommissioning process produced by ships.

The contribution of ship emissions to air quality problems in many areas around the world is increasing and numerous governments are considering how to address ship emissions at the local, national and international level.

The biggest part of the gaseous discharge occurring during vessel utilisation is represented by CO_2 emissions, which is related to the fuel consumed. Reducing those emissions means reducing fuel consumption, which in turn results in savings in fuel costs while addressing climate change (European Commission , 2013). Based on a report published by The International Council on Clean Transportation (ICCT) (2011) there are several technological and operational strategies to improve ship energy efficiency in order to reduce greenhouse gas (GHG) emissions.

For instance one of the most important components of the ship's efficiency is the propeller. The propeller transmits power by converting the rotational motion into thrust. Propeller upgrading in case of damage or regularly polishing and cleaning reduces the trailing turbulences and frictional losses to provide overall efficiency. The upgrade of a propeller mainly involves replacing the propeller or optimising the pitch of controllable pitch propellers. Another measure to increase engine efficiency are the Hull Coating and Cleaning, which includes the prevention and removal of marine biological growth in order to increase the energy efficiency by reduction of the frictional resistance resulting in less fuel consumption and CO_2 emissions. Thirdly, the most fuel-efficient route for long distances should be determined taking in account currents and weather forecasts as well as real time sea conditions. Furthermore air lubrication could be applied which refers to a technique which involves the pumping of compressed air into a recess of the bottom of the ship's hull over the length, to reduce frictional resistance between the water and the hull resulting in lower power demand. As a great factor in reducing fuel consumption speed reduction is proposed with 15 % to 19 % potential abatement for a speed reduction of 10 %. In addition wind engines, solar panels and waste heat recovery are proposed measures for alternative energy generating to reduce fuel consumption and associated CO_2 emissions. Overall, it is important to maintain the vessel's engine in good condition as the aged and faulty one consumes more fuel and emit a greater amount of gases.

Already in 1997, MARPOL, the International Convention for the Prevention of Pollution from Ships, was developed through the International Maritime Organisation as the main international agreement addressing air pollution from ocean-going ships. Limits on nitrogen oxides (NOx) emissions and requirements concerning the use of fuel with lower sulphur content were established in Annex VI in order to protect people's health and the environment by reducing ozone-producing pollution. Besides that, in the United States the annex includes the requirement, that each regulated diesel engine in vessels must have an Engine International Air Pollution Prevention (EIAPP) certificate and that the operators have to maintain records on board regarding their compliance with among others the emissions standards and fuel requirements (United States Environmental Protection Agency (EPA), 2013). It is widely acknowledged by marine engine manufacturers that different technologies exist which may enable significant improvements regarding the gaseous discharge. According to the Marine Environment Protection Committee

(2005) the industry has been engaged in the development of more advanced emission control technologies for marine diesel engines in awhile, such as combustion optimisation, advanced fuel injection control and electronic controls. Tecnologies for reducing NO_x include introducing water into the combustion process, NO_x adsorbers and selective catalytic reduction. The primary technique for reducing SO_x emissions is to reduce the sulfur content of the fuel used as those emissions only can be formed if there is sulfur present in the exhaust. Another investigated technology which is still experimental in marine applications, is exhaust gas scrubbing, where the gaseous emssions are mixed with sea water in order to be absorbed (Marine Environment Protection Commitee, 2005).

In further researches the stated technologies could be investigated and applied to marine diesel engines in order to reduce NO_x and SO_x emissions. In addition, also in Malaysia, requirements including limits for gaseous emissions could be implemented to encourage the development of new marine-specific technologies in order to reduce the environmental impacts, in this case associated with offshore decommissioning and the related vessel utilisation.

It becomes clear that there are already several technologies and possibilities available to reduce energy consumption and gaseous emissions related to the vessel utilisation during the decommissioning process. Additionally, already during the planning phase of a project, the travel distances to the decommissioning and artificial reef site as well as to the fabrication yard and the recycling or disposal site should be considered properly to be able to reduce the fuel consumption. Besides that, a proper estimation of materials and their weights should be established in order to choose the appropriate size of the vessel and the crane to avoid fuel and energy wastage. Moreover, the decommissioning of platforms as a group could affect the fuel consumption positively if the process is logistical and planned effectively.

4.4 SUMMARY

In this chapter the results of process based- and EIO-LCA were presented in table and graph format and further explained, interpreted and discussed. The decommissioning activity which is the main contributor to energy consumption and gaseous emissions was identified. Furthermore, relevant mitigation measures for environmental concerns were suggested. The following chapter will comprise the conclusion of the present study, recommendations on offshore decommissioning and life cycle assessment in general as well as recommendations for future research.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In the upcoming years the number of offshore oil and gas installations which have to be decommissioned, is going to increase around the world**,** as they approach the end of their productive lifetime. Due to the fact that decommissioning of offshore installations definitely causes harm to the marine life and the environment, in the present study, the environmental impacts focused on atmospheric emissions (CO_2, NO_x and SO_2) and the energy consumption induced by two different decommissioning options for offshore structures, complete removal and the development of an artificial reef are taken into account and assessed by using LCA tools: process based method and EIO method.

For this paper, data from the BPEO decommissioning Study for the Offshore Structure Platform A, located in the South China Sea, a cost estimation and various documentation documents about its decommissioning process, can be used as input data to perform LCA analysis. On the other hand, the EIO model is considered as more detailed, reliable and accurate since it has broad boundaries and takes the circularity effects, which should be counted in the real industry, into account. The outcome using this tool is that the energy consumption and the discharge of gaseous emissions are higher for the decommissioning option complete removal. Meanwhile, by conducting process based LCA analysis the opposite results were found, whereas conversion to an artificial reef consumes more energy and produces more harmful gases especially due to the bigger amount of vessel utilisation, which is identified as the decommissioning activity with the greatest contribution to the concerned parameters.

Furthermore, in the present study the determined results, regarding the total energy consumption and gaseous emissions, caused by decommissioning Platform A are compared to the parameters of decommissioning Heather Platform in the North Sea. A trend can be observed regarding the differences in energy consumption and gaseous emissions of the two totally different installations. However, to be able to justify the coherences, differences and a ratio between the results further studies have to be established. Due to limited availability of data and lack of samples for decommissioning in Malaysia it is not possible to issue an accurate statement if the found similarity is overall applicable to estimate the energy consumption and gaseous emissions for other decommissioning projects by simple use of a local unit rate. The results gathered from the two LCA analyses follow a similar trend although different data were input and the tools provide different perspectives. Both LCA tools are capable for evaluating the environmental impacts associated with offshore decommissioning depending on the availability of data. Process based method may be the more appropriate LCA tool in the present study, as the assumptions considered the real conditions, the size and existing materials of the selected case study, and several decommissioning activities were implemented.

Due to the finding that marine vessel utilisation is the greatest contributor to all the concerned parameters some mitigation measures could be suggested. Those are for instance the reduction of the travel distances and the reduction of the fuel by increasing the efficiency of marine vessel's engines. Furthermore the reduction of NO_x and SO_x emissions by applying advanced technologies and reducing the sulphur content in the fuel respectively.

In conclusion, the objectives of this study, such as identifying, quantifying and assessing the environmental impacts associated with the decommissioning of offshore platforms, using LCA tools, and suggesting of relevant mitigation measures, have been achieved.

5.2 RECOMMENDATIONS

5.2.1 RECOMMENDATIONS ON OFFSHORE DECOMMISSIONING

In order to reduce environmental impacts caused by offshore decommissioning the planning stage should be properly managed to minimise uncontrolled risks and reduce cost while addressing environmental concerns, decommissioning technology and platform characteristics. The decommissioning process has to be in compliance with the current legislation and international guidelines, onshore disposal of materials which are prohibited to left at sea and according to requirements regarding the removal of materials which could generate debris at the decommissioning site.

By adequately planning and executing the removal of the offshore structure the owner would not been exposed to undesired events or any future residual liability and maintenance needs would be eliminated. During the development of the decommissioning plan none of these issues should be considered in isolation but a balance between the various factors need to be established in order to find the appropriate and cost effective decommissioning scheme by adapting lateral thinking and existing technology. Post decommissioning survey immediately following the completion of the decommissioning process should be performed to define and document the condition and stability of the remaining structural materials (Hustoft & Gamblin, 1995).

The rigs to reef concept had been introduced and applied by several operators for offshore decommissioning operators as it was considered as the more appropriate option (Wan Abdullah Zawawi et al., 2012). Previous studies mention that the conversion to an artificial reef reduces costs, energy and gaseous emissions due to reduction of marine vessel utilisation and fuel consumption. Furthermore it is considered as more environmental friendly as the structural material which is left at sea provides habitant and protection for marine life (Ngu Pei Jia, 2013). This alternative for the re-use of offshore structures, which approach the end of their productive life, is still considered as a new option around the globe. The findings of this research performing process based LCA proves that the conversion to an artificial reef is not automatically the better decommissioning option in terms of energy consumption and gaseous emissions and that the cost might also be higher than for complete removal due to long travel distances and great amount of vessel utilisation. More researches need to be executed to investigate the benefits, side effects and environmental impacts caused by this decommissioning option depending on the platform size, location, surrounding conditions as well as the effects of monitoring and maintenance issues.

5.2.2 RECOMMENDATIONS ON LIFE CYCLE ASSESSMENT

For the future implementation of life cycle assessment in the evaluation of environmental impacts associated with decommissioning of offshore structures, it is recommended to have a complete set of detailed and relevant data among others of cost, platform characteristics, structural data, travel distances and vessel utilisation for conducting LCA analysis and to reduce the amount of assumptions applied in this study. Poor and incomplete data limits the validity and reduces the accuracy of the result. The uncertainty and sensitivity analysis could be carried out, if a complete set of reliable and relevant data is available and implemented. Then the important variables could be identified properly and the results could be verified.

During the goal and scope definition stage of life cycle assessment the objectives of the study, the scope and the boundaries have to be clearly defined. To ensure consistency and transparency the assumptions and the methodology need to be consistent and documented. There are still a lot of potential users who are not exposed to LCA and its benefits to improve their companies' operations. Awareness should be spread and more LCA researches should be conducted and published to increase the amount of information, to get reliable results which can be used in future assessments and to promote the use of LCA.

5.2.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The findings from this paper could serve as a basic framework to be used in the near future to assess the environmental impacts associated with offshore decommissioning activity in Malaysia by using LCA analysis. The results obtained by comparing the different structures and the parameters determined by using the LCA tools may be advantageous for other projects with similar conditions, regarding the possibility to reduce environmental impacts. Additionally, the values found in this research could provide incentive and motivation to find more efficient methods and new technologies for the decommissioning of offshore platforms, protecting the environment in future generation's interest.

5.3 SUMMARY OF CONTENT

Comprehensively this dissertation defined the background, problem statement, Objectives and Scope of Study for the Final Year Project with the title: "Comparative Assessment of Environmental Impacts Associated with the Decommissioning of Offshore Fixed Platforms". Additionally a literature review mentioning the topics offshore platform types, decommissioning of offshore platforms, life cycle assessment, the used case study Platform A and Heather Platform was stated. Afterwards the research methodology, project activities, key milestones and the planned schedule were provided. Subsequently, the LCA methodology including the applied assumptions for process based- and EIO-LCA was described. Additionally, the results of the study were presented, discussed and interpreted. Finally, mitigation measures related to marine vessel utilisation as well as recommendations on offshore decommissioning and life cycle assessment in general and for future research were given.

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APPENDICES

PROCESS BASED METHOD

APPENDIX A: UNIT CONVERSION FACTORS & REFERENCES

Conversion	Unit Conversion Factor		Source / Reference
Steel Plate and Shape From Ore	Energy Consumption	19 GJ/t	Ogivile (1992), Iron and Steel Institute (1990), Philip et al (1995)
	SO_2 Emissions	2 kg/t	
	NO_x Emissions	1.5 kg/t	
	Equivalent CO_2	60 kg/t	
	CO_2 Emission	2200 kg/t	
Steel Plate and Shape From Scrap	Energy Consumption	5 GJ/t	Ogivile (1992), Iron and Steel Institute (1990), Philip et al (1995)
	SO_2 Emissions	1.4 kg/t	
	NO_x Emissions	1 kg/t	
	Equivalent CO_2	40 kg/t	
	CO_2 Emission	360 kg/t	
Engine Diesel	Calorific Value	45.5 GJ/t	Munday and Farrar (1989), Brown and Root (1993)
	SO_2 Emissions	5 kg/t	
	NO_x Emissions	5.8 kg/t	
	Equivalent CO_2	238 kg/t	
	CO_2 Emission	3100 kg/t	
Marine Diesel	Calorific Value	45.4 GJ/t	Munday and Farrar (1989), Bouscaren (1990), Van Der Most (1990), Alexandersson (1990), Melhus (1990)
	SO_2 Emissions	45 kg/t	
	NO_x Emissions	45 kg/t	
	Equivalent CO_2	1905 kg/t	
	CO_2 Emission	3100 kg/t	
Propane	Calorific Value	50 GJ/t	Munday and Farrar (1989)
	SO_2 Emissions	0 kg/t	
	NO_x Emissions	3 kg/t	
	Equivalent CO_2	120 kg/t	
	CO_2 Emission	3007 kg/t	

APPENDIX B: DATA VARIABLES

Transportation Offshore (Workbarge, Anchor Handling Tug, Support Vessel, Dumb Barge, Supply Boat)	Travel Distance
	Use Duration
Section Cuttings	Oxy-Acetylene Cutting
	Abrasive Water Jet Cutting
	Diamond Wire Cutting
Boat Landing Dismantling Offshore [tonnes]	Structural Steel
	Marine Growth
Topside Dismantling Offshore [tonnes]	Structural Steel
	Timber
	Miscellaneous Materials
Jacket Dismantling Offshore [tonnes]	Sructural Steel
Jacket Dismantling Onshore [tonnes]	Marine Growth
Total Dismantling [tonnes]	Structural Steel
	Timber
	Marine Growth
	Miscellanous Materials
Recycling Onshore [tonnes]	Steel
Disposal Onshore [tonnes]	Timber
	Marine Growth
	Miscellaneous materials
Materials left at Sea	Jacket
	Boat Landing
	Marine Growth
	Mudmat (Timber)
Transportation Onshore	Travel Distance

APPENDIX C: HAULAGE CONSTANTS AND FACTORS

	Value	
Onshore Haulage Roundtrip Distance		
Port Pasir Gudang (Johor) to Fabrication Yard [miles]	6.21	10 km
Fabrication Yard to Scrap Dealer [miles]	24.86	40 km
Fabrication Yard to Landfill for Disposal (Pasir Gudang) [miles]	12.43	20 km
Onshore Haulage Factors		
Average truck fuel consumption [litre /mile]	1.8	
Average truck fuel weight [t/litre]	0.00085	
Average truck load [tonne]	20	
Additional percentage fuel consumption allowance for loading and offloading [%]	10	
Offshore Roundtrip Distance		
Singapore Port to Labuan Port [miles]	776.75	1250 km
Port (Labuan) to Platform Site [miles]	31.07	50 km
Platform Site to Artificial Reef Site [miles]	279.63	450 km
Platform Site to Fabrication Yard (Johor) [miles]	745.68	1200 km
Offshore Haulage Factor		
Average vessel fuel consumption [tonne marine diesel oil/mile]	0.035	
Maximun cargo capacity [tonnes]	500	
Additional percentage fuel consumption allowance for loading and offloading [%]	20	

Scrap Dealer
Empoline Corporation Sdn Bhd
No. 11 Jln Bukit Kempas 4/1,
Taman Bukit Kempas,
81200 Johor Bahru, Malaysia

Fabrication Yard
Sime Sembcorp Engineering Sdn Bhd
Plo 336 Jalan Suasa
81707 Pasir Gudang
Malaysia

APPENDIX D: UNIT CONVERSION FACTORS DISMANTLING

	Propane Consumption [kg/tonne]
Topsides Piecesmall Dismantling Offshore	
Structural steel	2.40
Timber	0
Miscellanceous materials	0
Jacket Dismantling Offshore	
Steel	2.40
Marine Growth	0
Boat Landing Dismantling Offshore	
Steel	2.40
Removal of Marine Growth Onshore	2.40

APPENDIX E: AVERAGE DAILY FUEL CONSUMPTION OF VESSELS

	In Port	In Transit	Working	Waiting on Weather (W.O.W)
Anchor Handling Tug (AHT)	2	10	10	10
Support Vessel	2	20	25	25
Workbarge	2	10	10	10
Dumb Barge	2	15	15	15
Supply Boat	2	10	5	5

[tonnes marine diesel/day]

APPENDIX F: CALCULATION MARINE VESSEL UTILISATION

COMPLETE REMOVAL

			in Port			in Transit			Working			Waiting on Weather (W.O.W)			
	Number	Duration [days]	Duration [days]	Fuel Consumption [t/day]	Fuel Consumption [t]	Duration [days]	Fuel Consumption [t/day]	Fuel Consumption [t]	Duration [days]	Fuel Consumption [t/day]	Fuel Consumption [t]	Duration [days]	Fuel Consumption [t/day]	Fuel Consumption [t/day]	Total Fuel Consumtion [t/type]
WorkBarge	1	10	0	2	0	2	10	20	8	10	80	0	10	0	100
Anchor Handling Tug (DB)	1	25	8	2	16	1	10	10	16	10	160	0	10	0	186
Anchor Handling Tug (WB)	1	10	7	2	14	1	10	10	2	10	20	0	10	0	44
Support Vessel	1	13	3	2	6	1	20	20	9	25	225	0	25	0	251
Dumb Barge	1	25	1	2	2	16	15	240	8	15	120	0	15	0	362
Supply Boat	1	10	0	2	0	10	10	100	0	5	0	0	5	0	100

Total Fuel Consumption [t]	1043

	Number	Average vessel Fuel Consumtion [t/mile]	Port (Labuan) to Platform Site [miles]	Platform Site to Port (Johor) [miles]	Port Johor to Port Labuan [miles]	Number of Ways: Labuan to Site	Number of Ways: Site to Johor	Number of Ways: Johor to Labuan	Travel Distance [miles]	Fuel Consumption [t]
WorkBarge	1	0.035	31.07	745.68	745.68	2	0	0	62.14	2.1749
Anchor Handling Tug (DB)	1	0.035	31.07	745.68	745.68	4	1	1	1615.64	56.5474
Anchor Handling Tug (WB)	1	0.035	31.07	745.68	745.68	4	0	0	124.28	4.3498
Support Vessel	1	0.035	31.07	745.68	745.68	2	0	0	62.14	2.1749
Dumb Barge	1	0.035	31.07	745.68	745.68	1	1	1	1522.43	53.28505
Supply Boat	1	0.035	31.07	745.68	745.68	20	0	0	621.4	21.749

Total Fuel Consumtion [t]	140.28

ARTIFICIAL REEF

			in Port			in Transit			Working			Waiting on Weather (W.O.W)			
	Number	Duration [days]	Duration [days]	Fuel Consumption [t/day]	Fuel Consumption [t]	Duration [days]	Fuel Consumption [t/day]	Fuel Consumption [t]	Duration [days]	Fuel Consumption [t/day]	Fuel Consumption [t]	Duration [days]	Fuel Consumption [t/day]	Fuel Consumption [t/day]	Total Fuel Consumtion [t/type]
WorkBarge	1	25	0	2	0	16	10	160	9	10	90	0	10	0	250
Anchor Handling Tug (DB)	1	15	8	2	16	1	10	10	6	10	60	0	10	0	86
Anchor Handling Tug (WB)	1	25	8	2	16	1	10	10	16	10	160	0	10	0	186
Support Vessel	1	13	3	2	6	1	20	20	9	25	225	0	25	0	251
Dumb Barge	1	15	1	2	2	6	15	90	8	15	120	0	15	0	212
Supply Boat	1	10	0	2	0	10	10	100	0	5	0	0	5	0	100

Total Fuel Consumption [t]	1085

	Number	Average Vessel Fuel Consumtion [t/mile]	Port (Labuan) to Platform Site [miles]	Platform Site to Port (Johor) [miles]	Port Johor to Port Labuan [miles]	Platform Site to Artificial Reef Site [miles]	Artificial Reef Site to Port Labuan [miles]	Number of Ways: Labuan - Site	Number of Ways: Site - Johor	Number of Ways: Johor - Labuan	Number of Ways: Platform Site - Artificial Reef Site	Number of Ways: Artificial Reef - Labuan Port	Travel Distance [miles]	Fuel Consumption [t]
WorkBarge	1	0.035	31.07	745.68	745.68	279.63	279.63	1	1	1	0	0	1522.43	53.29
Anchor Handling Tug (DB)	1	0.035	31.07	745.68	745.68	279.63	279.63	3	0	0	1	1	652.47	22.84
Anchor Handling Tug (WB)	1	0.035	31.07	745.68	745.68	279.63	279.63	3	1	1	0	0	1584.57	55.46
Support Vessel	1	0.035	31.07	745.68	745.68	279.63	279.63	2	0	0	0	0	62.14	2.17
Dumb Barge	1	0.035	31.07	745.68	745.68	279.63	279.63	1	0	0	1	1	590.33	20.66
Supply Boat	1	0.035	31.07	745.68	745.68	279.63	279.63	20	0	0	0	0	621.40	21.75

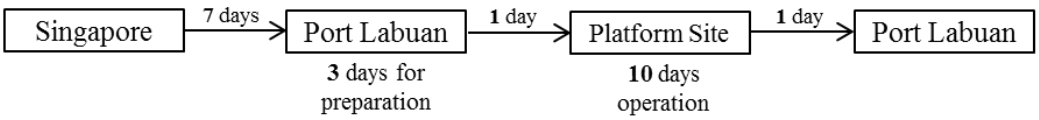
Total Fuel Consumtion [t]	176.17

Overall Fuel Consumtion (Marine Vessel Utilisation) [t]	Total Energy Consumtion [GJ]	SO_2 Emissions [kg]	No_x Emissions [kg]	CO_2 Emissions [kg]	Equivalent CO_2 Emissions [kg]	Overall CO_2 Emissions [kg]	
1183.28	53,720.96	53,247.65	53,247.65	3,668,171.26	2,254,150.40	5,922,321.66	**Complete Removal**
1261.17	57,256.98	56,752.51	56,752.51	3,909,617.39	2,402,522.94	6,312,140.33	**Artificial Reef**
77.89	3,536.02	3,504.86	3,504.86	241,446.13	148,372.54	389,818.68	**Difference [unit]**
6.18	6.18	6.18	6.18	6.18	6.18	6.18	**Difference[%]**

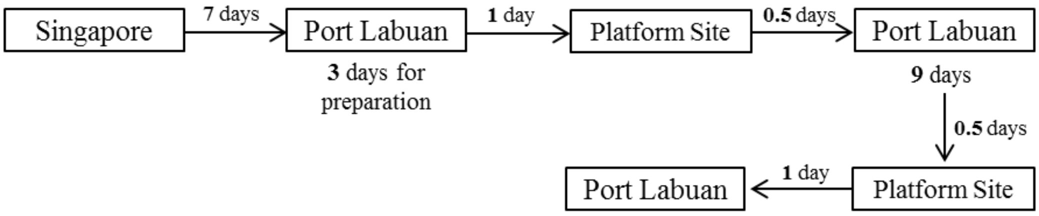
APPENDIX G: FIGURES SHOWING VESSEL TYPES WITH DURATION AND KIND OF USE

COMPLETE REMOVAL

Work Barge (22 days)

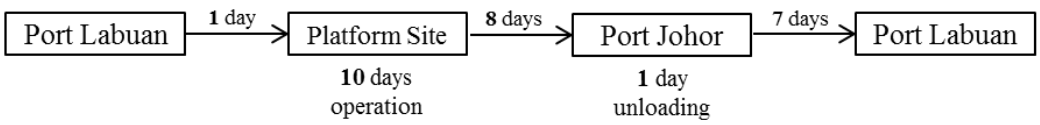


2 AHT for Work Barge (22 days)

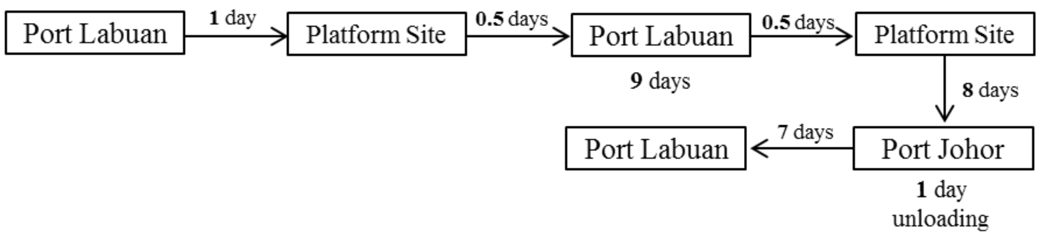


Supply Boat (10 days)

Dumb Barge (27 days)



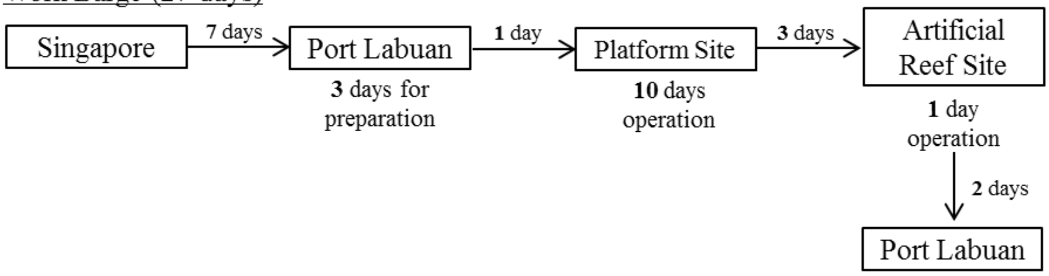
2 AHT for Dumb Barge (27 days)



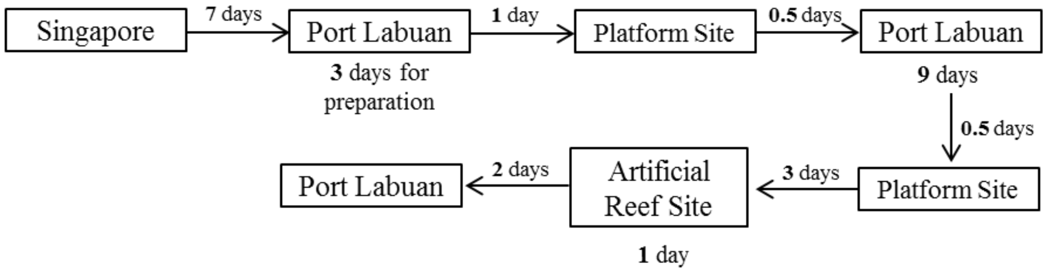
Support Vessel (11 days)

ARTIFICIAL REEF

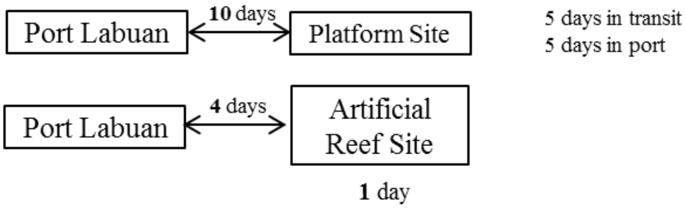
Work Barge (27 days)



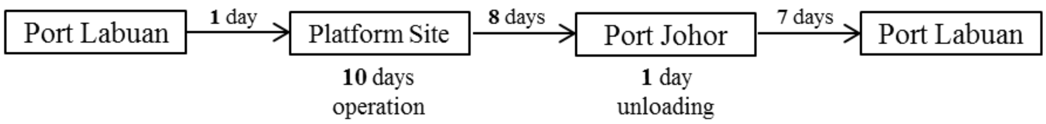
2 AHT for Work Barge (27 days)



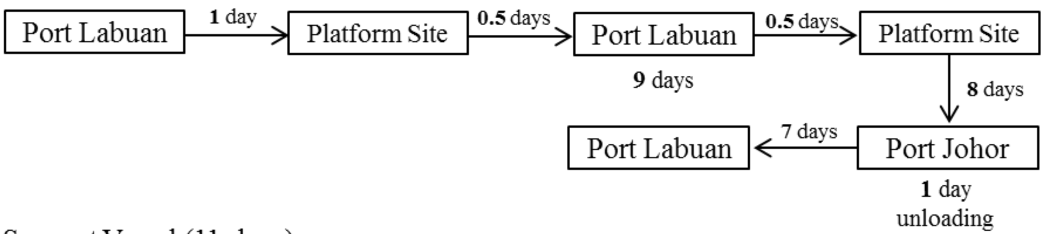
Supply Boat (15 days)



Dumb Barge (27 days)



2 AHT for Dumb Barge (27 days)



Support Vessel (11 days)

APPENDIX H: CALCULATION PLATFORM DISMANTLING

COMPLETE REMOVAL

Marine Growth: 11.76 % of Jacket Weight *(according to Heather Platform)*

Offshore

Component	Material	Weight [t]	Cutting Method	Propane Consumption [kg/t]	Propane Consumption [kg]
Boat Landing	Steel	16.00	Oxy-Acetylene Cutting	2.40	38.40
Topside	Steel	21.40	Abrasive Water Jet Cutting	2.40	51.36
	Timber	5.60	Saw	0	0.00
	Miscellaneous	1.00	Others	0	0.00
Jacket	Steel	32.50	Diamond Wire Cutting	2.40	78.00
Conductor	Steel	27.90	Diamond Wire Cutting	2.40	66.96

Onshore

Component	Weight	Cutting Method	Propane Consumption [kg/t]	Propane Consumption [kg]
Marine Growth	3.82	Abrasive Water Jet Cutting	2.40	9.17

Total Propane Consumption [kg]	Total Propane Consumption [t]
243.89	0.24

ARTIFICIAL REEF

Offshore

Component	Material	Weight [t]	Cutting Method	Propane Consumption [kg/t]	Propane Consumption [kg]
Boat Landing	Steel	16.00	Oxy-Acetylene Cutting	TOWED TO AR-SITE	
Topside	Steel	21.40	Abrasive Water Jet Cutting	2.40	51.36
	Timber	5.60	Saw	0	0
	Miscellaneous	1.00	Others	0	0
Jacket	Steel	32.50	Diamond Wire Cutting	TOWED TO AR-SITE	
Conductor	Steel	27.90	Diamond Wire Cutting	2.40	66.96

Onshore

Component	Weight	Cutting Method	Propane Consumption [kg/t]	Propane Consumption [kg]
Marine Growth	3.82	NO REMOVAL	----	----

Total Propane Consumption [kg]	Total Propane Consumption [t]
118.32	0.12

Total Propane Consumption [t]	Total Energy Consumtion [GJ]	SO_2 Emissions [kg]	No_x Emissions [kg]	CO_2 Emissions [kg]	Equivalent CO_2 Emissions [kg]	Overall CO_2 Emissions [kg]	
0.24	12.19	0.00	0.73	733.39	29.27	762.65	**Complete Removal**
0.12	5.92	0.00	0.35	355.79	14.20	369.99	**Artificial Reef**
0.13	6.28	0.00	0.38	377.60	15.07	392.67	**Difference [unit]**
51.49	51.49	0.00	51.49	51.49	51.49	51.49	**Difference[%]**

APPENDIX I: CALCULATION PLATFORM MATERIALS RECYCLING

COMPLETE REMOVAL

Topside Weight (incl. Timber, Miscellaneous) [t]	Jacket Weight (incl. Marine Growth) [t]	Boat Landing Weight [t]	Conductor Weight [t]	Timber [t]	Marine Growth [t]	Miscellaneous [t]	Steel Recycling [t]
28.00	32.50	16.00	27.9	5.60	3.82	1.00	93.98

PLATFORM MATERIALS RECYCLING
ARTIFICIAL REEF

Topside Weight (incl. Timber, Miscellaneous) [t]	Jacket Weight (incl. Marine Growth) [t]	Boat Landing Weight [t]	Conductor Weight [t]	Timber [t]	Marine Growth [t]	Miscellaneous [t]	Steel Recycling [t]
28.00	---	---	27.9	5.60	3.82	1.00	49.30

Total Steel Recycling [t]	Total Energy Consumtion [GJ]	SO_2 Emissions [kg]	No_x Emissions [kg]	CO_2 Emissions [kg]	Equivalent CO_2 Emissions [kg]	Overall CO_2 Emissions [kg]	
93.98	469.90	131.57	93.98	33,832.80	3,759.20	37,592.00	**Complete Removal**
49.30	246.50	69.02	49.30	17,748.00	1,972.00	19,720.00	**Artificial Reef**
44.68	223.40	62.55	44.68	16,084.80	1,787.20	17,872.00	**Difference [unit]**
47.54	47.54	47.54	47.54	47.54	47.54	47.54	**Difference[%]**

APPENDIX J: CALCULATION PLATFORM MATERIALS LEFT AT SEA

COMPLETE REMOVAL

Assumptions:
- Mudmat (Timber) is left at the Sea -> not considered in the calculation

ARTIFICIAL REEF

Assumptions:
- Mudmat (Timber) is left at Sea -> not considered in the calculation
- Marine Growth not removed and left at sea -> not considered in the calculation
- Jacket and Boat Landing are towed to the Artificial Reef Site and left at sea
  -> Considered in the calculations using conversion factors "Steel Plate and Schape from Ore"

Topside Weight (incl. Timber, Miscellaneous) [t]	Jacket Weight (incl. Marine Growth) [t]	Boat Landing Weight [t]	Conductor Weight [t]	Timber [t]	Marine Growth [t]	Miscellaneous [t]
28.00	32.50	16.00	27.9	5.60	3.82	1.00

Steel left at Sea [t]
48.50

Total Steel Left at Sea [t]	Total Energy Consumtion [GJ]	SO_2 Emissions [kg]	No_x Emissions [kg]	CO_2 Emissions [kg]	Equivalent CO_2 Emissions [kg]	Overall CO_2 Emissions [kg]	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	**Complete Removal**
48.50	921.50	97.00	72.75	106,700.00	2,910.00	109,610.00	**Artificial Reef**

48.50	921.50	97.00	72.75	106,700.00	2,910.00	109,610.00	**Difference [unit]**
100.00	100.00	100.00	100.00	100.00	100.00	100.00	**Difference[%]**

APPENDIX K: CALCULATION TRANSPORTATION ONSHORE

COMPLETE REMOVAL

Truck Load: 20 tonnes

Topside Weight (incl. Timber, Miscellaneous) [t]	Jacket Weight (incl. Marine Growth) [t]	Boat Landing Weight [t]	Conductor Weight [t]	Timber [t]	Marine Growth [t]	Miscellaneous [t]
28.00	32.50	16.00	27.9	5.60	3.82	1.00

Steel Recycling [t]	Disposal [t]	Number of Trucks Recycling	Number of Trucks Disposal	Distance Port Pasir Gudang to Fabrication Yard [miles]	Distance Fabrication Yard to Scrap Dealer [miles]	Distance Fabrication Yard to Disposal Site [miles]	Total Distance for Recycling [miles]	Total Distance for Disposal [miles]
93.98	10.42	5	1	6.21	24.86	12.43	310.7	37.28

Average Truck Diesel Consumtion [litre/mile]	Average Weight Engine Diesel [t/litre]	Additional Pecentage [%]	Total Distance for Recycling [miles]	Total Distance for Disposal [miles]	Total Diesel Consumption [tonnes]
1.8	0.00085	10	310.7	37.28	0.59

ARTIFICIAL REEF

Topside Weight (incl. Timber, Miscellaneous) [t]	Jacket Weight (incl. Marine Growth) [t]	Boat Landing Weight [t]	Conductor Weight [t]	Timber [t]	Marine Growth [t]	Miscellaneous [t]
28.00	TOWED TO AR-SITE	TOWED TO AR-SITE	27.9	5.60	NO REMOVAL	1.00

Steel Recycling [t]	Disposal [t]	Number of Trucks Recycling	Number of Trucks Disposal	Distance Port Pasir Gudang to Fabrication Yard [miles]	Distance Fabrication Yard to Scrap Dealer [miles]	Distance Fabrication Yard to Disposal Site [miles]	Total Distance for Recycling [miles]	Total Distance for Disposal [miles]
49.30	6.60	3	1	6.21	24.86	12.43	186.42	37.28

Average Truck Diesel Consumtion [litre/mile]	Average Weight Engine Diesel [t/litre]	Additional Pecentage [%]	Total Distance for Recycling [miles]	Total Distance for Disposal [miles]	Total Fuel Consumption [tonnes]
1.8	0.00085	10	186.42	37.28	0.38

Total Diesel Consumption [t]	Total Energy Consumtion [GJ]	SO_2 Emissions [kg]	No_x Emissions [kg]	CO_2 Emissions [kg]	Equivalent CO_2 Emissions [kg]	Overall CO_2 Emissions [kg]	
0.59	26.65	2.93	3.40	1,815.54	139.39	1,954.92	**Complete Removal**
0.38	17.13	1.88	2.18	1,167.13	89.61	1,256.74	**Artificial Reef**
0.21	9.52	1.05	1.21	648.41	49.78	698.19	**Difference [unit]**
35.71	35.71	35.71	35.71	35.71	35.71	35.71	**Difference[%]**

APPENDIX L: VARIATION OF ENERGY CONSUMPTION AND GASEOUS EMISSIONS DEPENDING ON DECOMMISSIONING ASPECT AND OPTION

Variable	Decommissioning Aspect	Complete Removal	Artificial Reef
Energy Consumption [GJ]	Marine Vessel Utilisation	36,596.52	36,959.72
	Platform Dismantling	12.19	5.92
	Platform Materials Recycling	469.90	246.50
	Platform Materials left at Sea	0.00	921.50
	Transportation Onshore	26.65	17.13
	All Decommissioning Aspects	**37,105.26**	**38,150.77**
SO_2 Emissions [Kg]	Marine Vessel Utilisation	36,274.09	36,634.09
	Platform Dismantling	0.00	0.00
	Platform Materials Recycling	131.57	69.02
	Platform Materials left at Sea	0.00	97.00
	Transportation Onshore	2.93	1.88
	All Decommissioning Aspects	**36,408.59**	**36,801.99**
NO_x Emissions [Kg]	Marine Vessel Utilisation	36,274.09	36,634.09
	Platform Dismantling	0.73	0.35
	Platform Materials Recycling	93.98	49.30
	Platform Materials left at Sea	0.00	72.75
	Transportation Onshore	3.40	2.18
	All Decommissioning Aspects	**36,372.19**	**36,758.67**
CO_2 Emissions [Kg]	Marine Vessel Utilisation	2,498,881.48	2,523,681.48
	Platform Dismantling	733.39	355.79
	Platform Materials Recycling	33,832.80	17,748.00
	Platform Materials left at Sea	0.00	106,700.00
	Transportation Onshore	1,815.54	1,167.13
	All Decommissioning Aspects	**2,535,263.20**	**2,649,652.40**
Equivalent CO_2 Emissions [Kg]	Marine Vessel Utilisation	1,535,602.97	1,550,842.97
	Platform Dismantling	29.27	14.20
	Platform Materials Recycling	3,759.20	1,972.00
	Platform Materials left at Sea	0.00	2,910.00
	Transportation Onshore	139.39	89.61
	All Decommissioning Aspects	**1,539,530.83**	**1,555,828.78**
Overall CO_2 Emissions [Kg]	Marine Vessel Utilisation	4,034,484.45	4,074,524.45
	Platform Dismantling	762.65	369.99
	Platform Materials Recycling	37,592.00	19,720.00
	Platform Materials left at Sea	0.00	109,610.00
	Transportation Onshore	1,954.92	1,256.74
	All Decommissioning Aspects	**4,074,794.03**	**4,205,481.18**

APPENDICES

EIO METHOD

APPENTIX M: ENERGY CONSUMPTION FOR EIO STANDARD UNIT MODEL

	Sector	Total Energy TJ
	Total for all sectors	*7.79*
213112	Support activities for oil and gas operations	2.11
221100	Power generation and supply	1.46
331110	Iron and steel mills	0.785
211000	Oil and gas extraction	0.493
327310	Cement manufacturing	0.412
324110	Petroleum refineries	0.259
484000	Truck transportation	0.211
325190	Other basic organic chemical manufacturing	0.172
322130	Paperboard Mills	0.135
486000	Pipeline transportation	0.113

APPENDIX N: OVERALL CO_2 EMISSIONS FOR EIO STANDARD UNIT MODEL

	Sector	Glob Warm kg CO2e
	Total for all sectors	*650000*
213112	Support activities for oil and gas operations	139000
221100	Power generation and supply	120000
211000	Oil and gas extraction	82300
327310	Cement manufacturing	71200
331110	Iron and steel mills	67700
484000	Truck transportation	15500
324110	Petroleum refineries	15500
212100	Coal mining	12500
325120	Industrial gas manufacturing	10400
486000	Pipeline transportation	9410

APPENDIX O: SO_2 AND NO_x EMISSIONS FOR EIO STANDARD UNIT MODEL

	Sector	NOx t	SO2 t
	Total for all sectors	*6.33*	*1.89*
213112	Support activities for oil and gas operations	5.03	0.886
331110	Iron and steel mills	0.050	0.038
532400	Commercial and industrial machinery and equipment rental and leasing	0.005	0.002
211000	Oil and gas extraction	0.152	0.010
327310	Cement manufacturing	0.196	0.144
221200	Natural gas distribution	0.006	0.002
484000	Truck transportation	0.136	0.003
331200	Iron, steel pipe and tube manufacturing from purchased steel	0.007	0.005
33131A	Alumina refining and primary aluminum production	0.002	0.015
333920	Material handling equipment manufacturing	0.011	0.000

APPENDIX P: COST INPUT DATA ARTIFICIAL REEF

Twachtman Snyder & Byrd, Inc. (2000). *State of the Art of Removing Large Platforms Located in Deep Water (Final Report).* Houston, Texas.

Platform	Water Depth [ft]	Jacket Weight [t]	Cost Complete Removal [$]	Cost Remote Reef [$]	Percentage Cost Remote Reefing of Complete Removal [%]	Average Difference [%]
Hidalgo	430	10,950	44,245,300	17,768,257	40.16	34.79
Gail	739	18,300	56,678,210	20,316,947	35.85	
Harmony	1198	42,900	123,295,033	34,976,168	28.37	

Cost Estimation by PETRONAS Petroleum Management Unit (PMU RM 27,187,304.25

35 % of Complete Removal Cost RM 9,515,556.49

APPENDIX Q: COMPARISON PROCESS BASED METHOD AND EIO METHOD

	EIO-Method			Process Based -Method		
Variable	Complete Removal	Conversion to Artificial Reef	Complete Removal Heather Platform	Complete Removal	Conversion to Artificial Reef	Complete Removal Heather Platform
Total Energy Consumtion [GJ]	69,022	24,158	1,516,168	37,105	38,151	939,479
SO_2 Emissions [kg]	16,746	5,861	1,232,008	36,409	36,802	631,674
No_x Emissions [kg]	56,086	19,630	367,851	36,372	36,759	624,318
Overall CO_2 Emissions [kg]	5,759,251	2,015,738	126,509,500	4,074,794	4,205,481	91,450,691

	Difference between Models [unit]		
Variable	Complete Removal	Conversion to Artificial Reef	Complete Removal Heather Platform
Total Energy Consumtion [GJ]	31,917	-13,993	576,689
SO_2 Emissions [kg]	-19,663	-30,941	600,334
No_x Emissions [kg]	19,714	-17,129	-256,467
Overall CO_2 Emissions [kg]	1,684,457	-2,189,743	35,058,809

	Difference between Models [%]		
Variable	Complete Removal	Conversion to Artificial Reef	Complete Removal Heather Platform
Total Energy Consumtion [GJ]	46	37	38
SO_2 Emissions [kg]	54	84	49
No_x Emissions [kg]	35	47	41
Overall CO_2 Emissions [kg]	29	52	28